CAMPUS DE EXCELENCIA INTERNACIONAL

Universidad Politécnica de Madrid

Recent research of the UPM Nuclear Safety Group with the GOTHIC code

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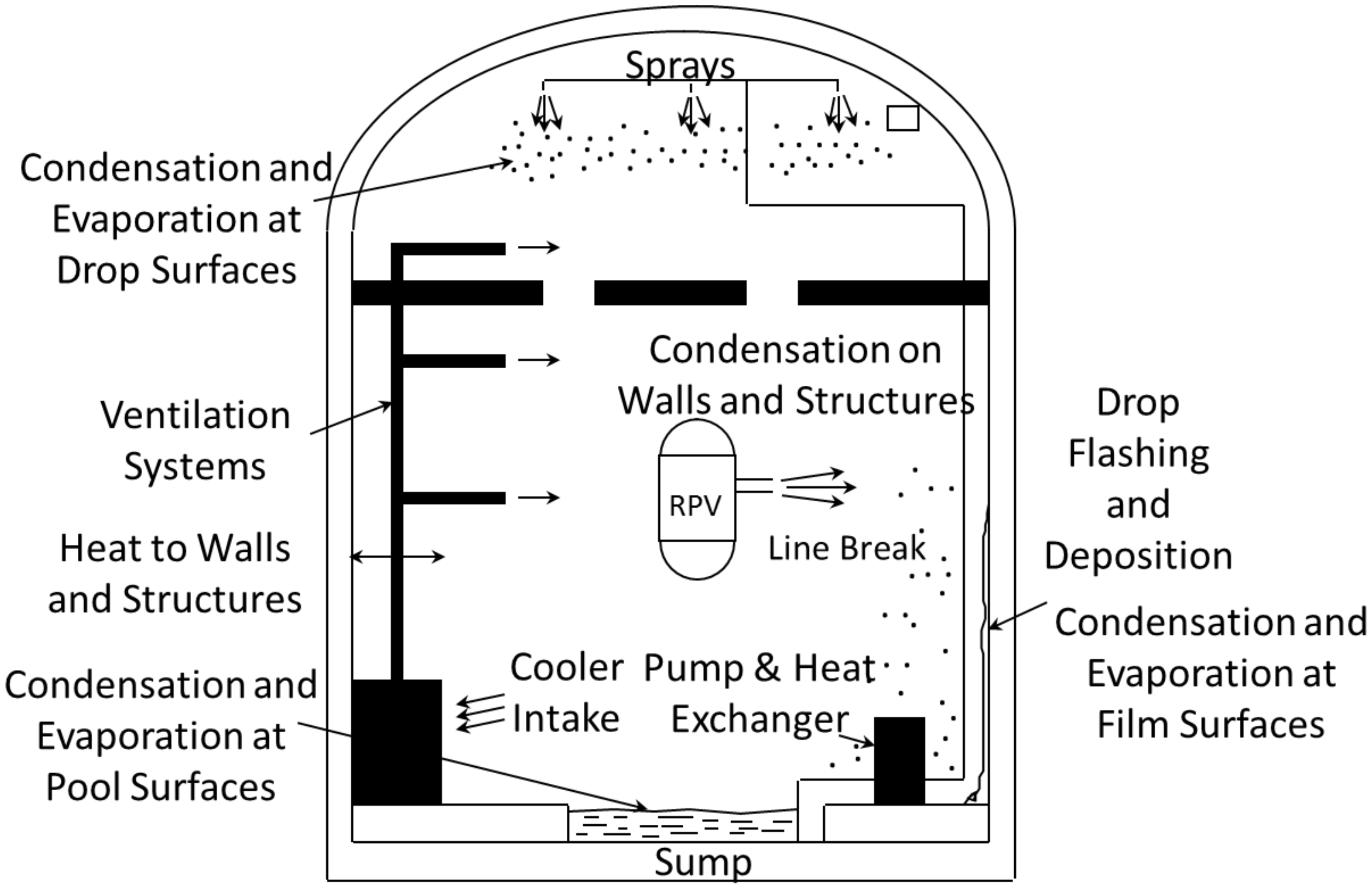
UPM and Nuclear Safety Group

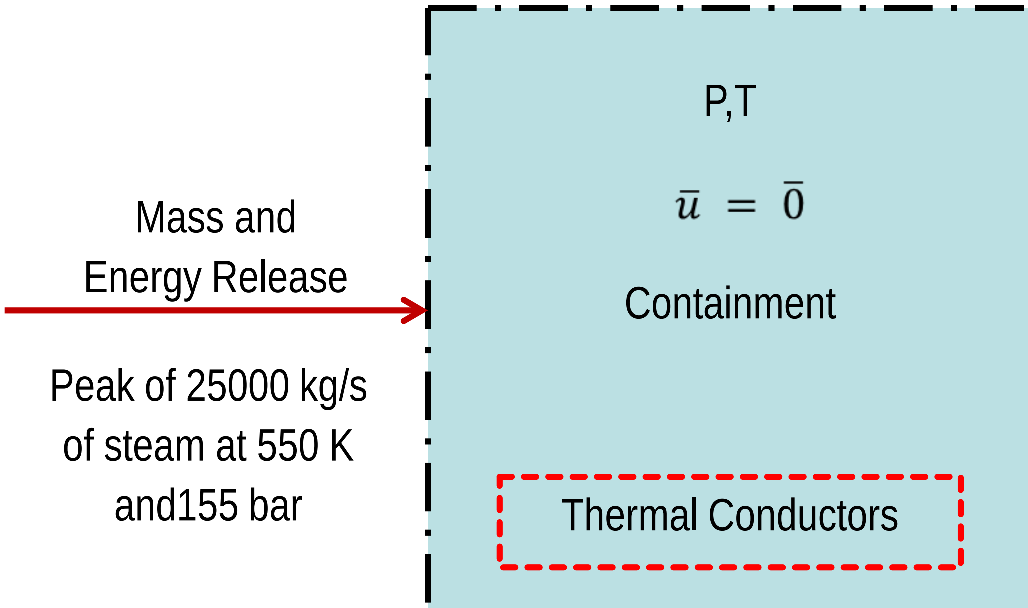
- UPM Nuclear Safety group:
  - Technical University of Madrid, Spain.
  - Research with the GOTHIC code since 2012.
  - Gonzalo Jiménez, Rafael Bocanegra, Samanta Estévez, Carlos Vázquez, Emma López-Alonso, César Queral, Kevin Fernández-Cosials.
  - Containment simulation is the cornerstone of the Group.



A Little bit of History



Lumped Parameters Approach



Lumped Parameters Approach Characteristics

- 1 or few computational cells
- 60000 m^3
- 2-3 phases (liquid, gas and drops)
- Several components (Steam, air, H_2, N_2).

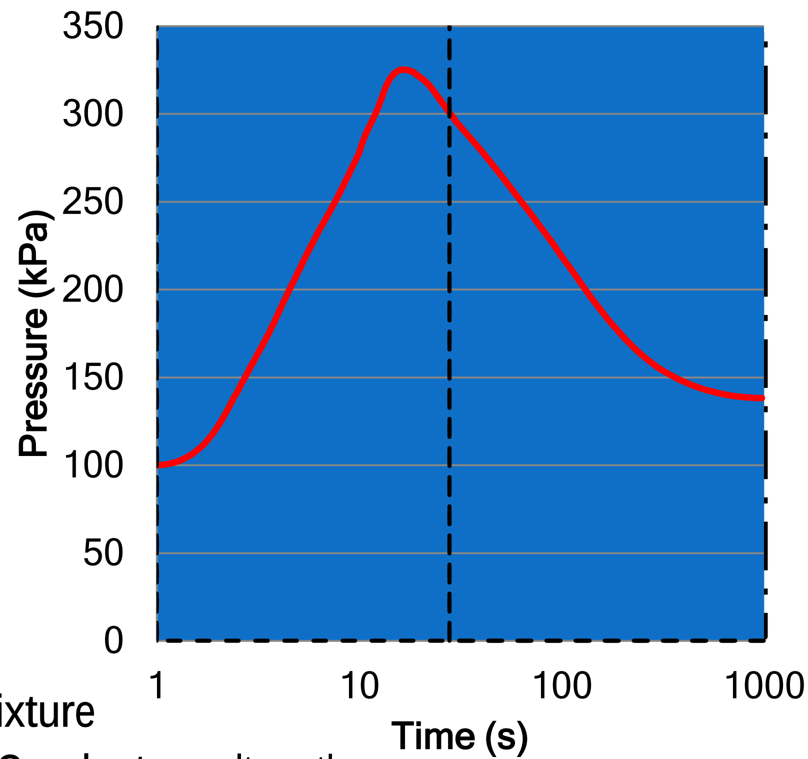
Simulation hypothesis

- Instant **Mixture**
- **Thermal Conductors** altogether
- **Velocity** is zero
- Sumps
- Spray

Examples of containment licensing with LPM

- Westinghouse Methodology (2013)
- Framatome Methodology (2004)
- Dominion Methodology (2006)

Lumped Parameters Approach



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Containment Acceptance Criteria

The US acceptance criteria in section 6.2.1.1.A of Standard Review Plan (SRP) requires that (the text is a sub-section):

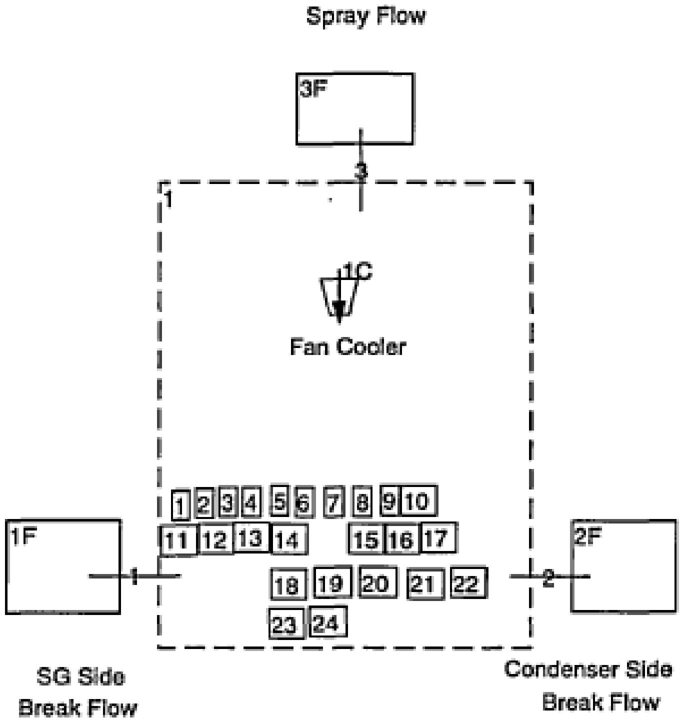
1. The **peak** calculated containment pressure following a postulated loss-of-coolant accident, or a steam or feedwater line break, should be **less than the containment design pressure.**
2. The containment pressure should be **reduced to less than 50%** of the peak calculated pressure for the design basis loss-of-coolant accident within 24 hours after the postulated accident.
3. **Instrumentation** capable of operating in the post-accident environment should be provided to monitor the containment atmosphere pressure and temperature and the sump water level and temperature following an accident.
4. Containment **internal structures and system components** (e.g., reactor vessel, pressurizer, steam generators) and supports should be designed to withstand the differential pressure loadings that may be imposed as a result of pipe breaks within the containment subcompartments.
5. In meeting the requirements of 10 CFR 50.34(f)(3)(v)(A)(1), applicants subject to this section should evaluate an accident that releases **hydrogen** generated from a 100% fuel clad metal-water reaction

Previous Applications

Example of a **containment GOTHIC model**:

- Prairie Island GOTHIC Containment Model scheme for MSLB Events. WCAP-16219-NP

Recently, GOTHIC is able to perform 3D simulations



UPM 3D modelling Capability

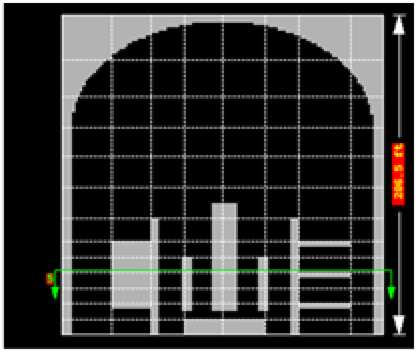
1. The GOTHIC code
2. General Approach to Containment Modelling
3. Detailed Integral modelling, Multi-zone/Nesting Dolls containment modelling and Geometrically Simplified Grid Adapted modelling
4. Application and model verification

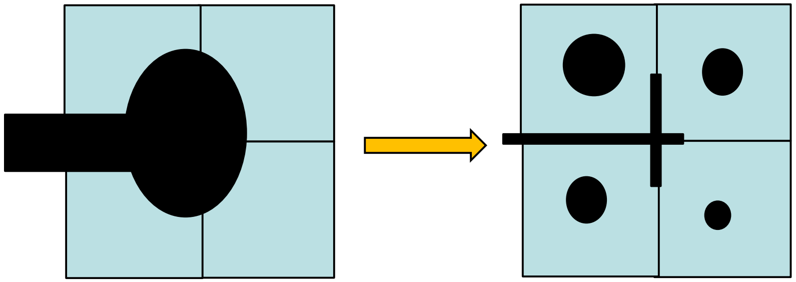
UPM 3D modelling Capability

- **GOTHIC code**:
  - Lumped Parameter or Multi-dimensional Modeling
  - Solves Conservation of Mass, Momentum, Energy for different phases, Eulerian-Eulerian approach.
  - Uses Correlations for heat transfer and friction (based on bulk values)
  - Can use different spatial discretization schemes and algorithms limiters.
  - Simulation Engineered Safety Equipment (Components)

UPM 3D modelling Capability

- **GOTHIC code**:
  - Uses a Cartesian mesh
  - Uses a porous approach to model geometries
  - Only certain geometries are allowed (wedges, cylinders, caps, torus)





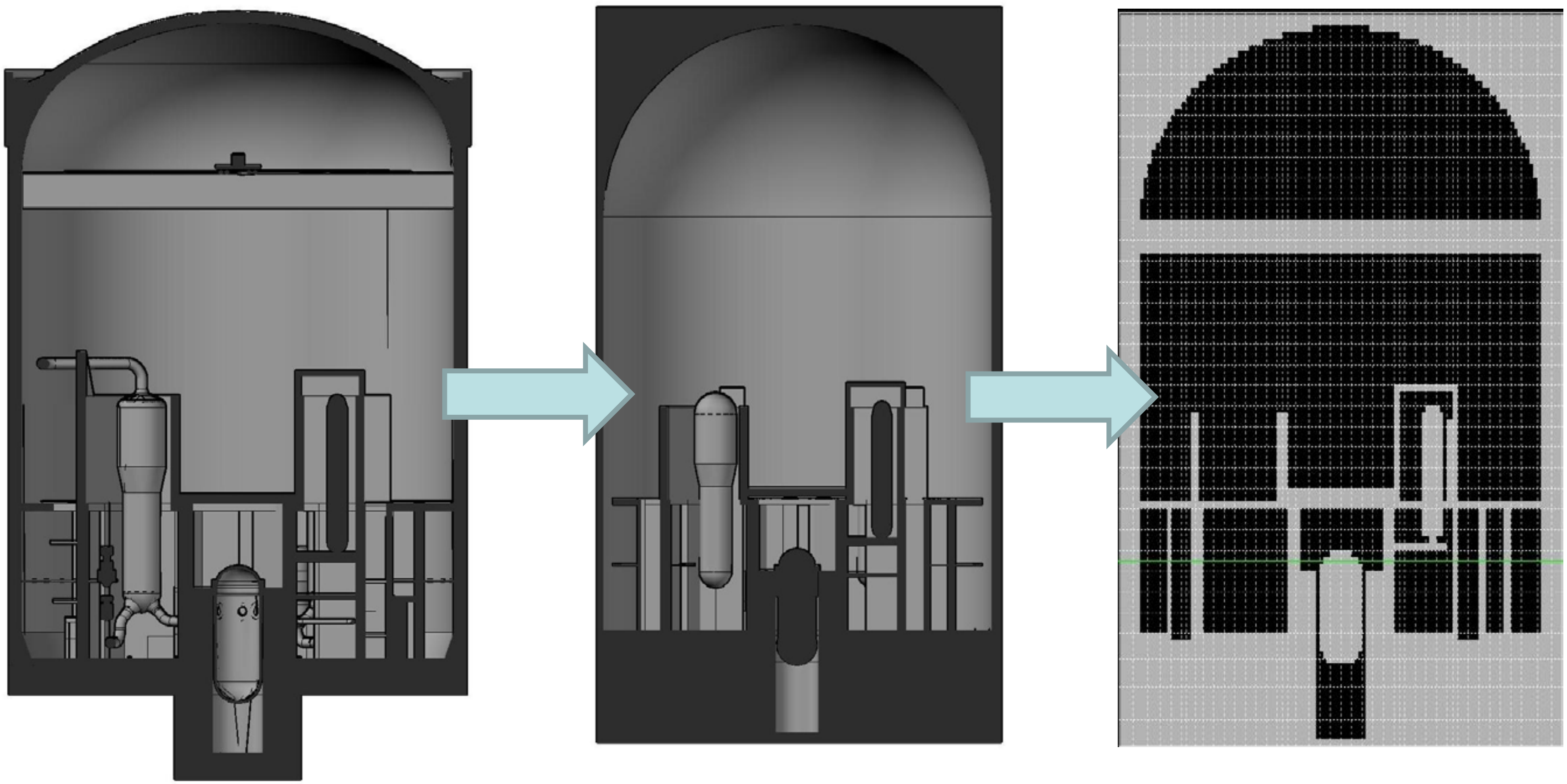
Indistinguishable for the code

UPM 3D modelling Capability

- **GOTHIC code**:
  - **GOTHIC has 3D CFD capabilities** (3D mesh, turbulence models (RANS)) with correlations for wall heat transfer and wall friction
  - GOTHIC allows to simulate a containment with less computational cost than a commercial CFD **BUT with some approximations** (wall heat transfer and wall friction)

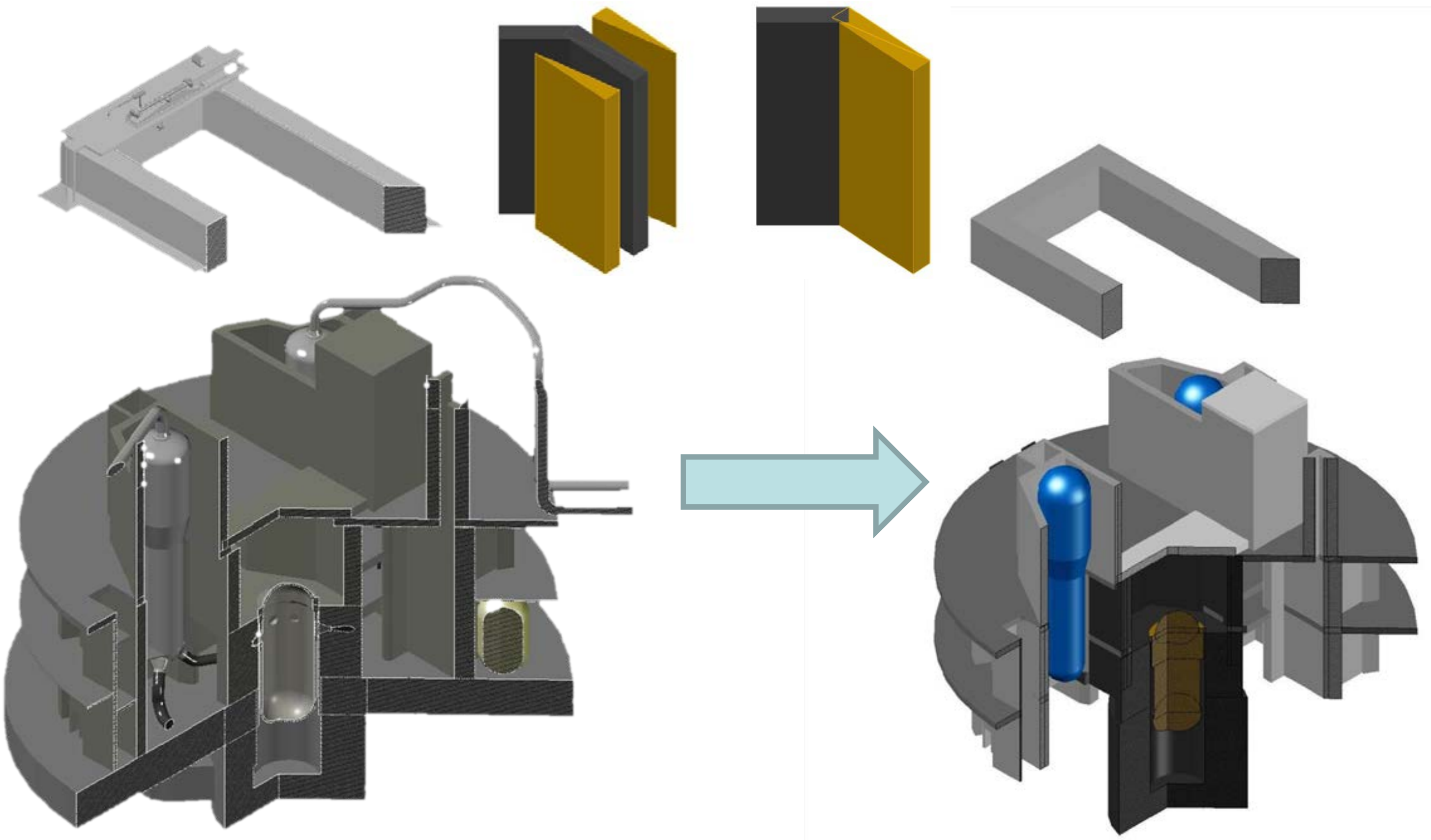
General approach to Containment Modelling

Detailed 3D CAD Model | Simplified 3D CAD Model | Thermal-Hydraulic Model



Ref: Bocanegra, R., Jimenez, G., Fernández-Cosials, M.K., 2016. Development of a PWR-W GOTHIC 3D model for containment accident analysis. Annals of Nuclear Energy 87, 547–560. https://doi.org/10.1016/j.anucene.2015.10.022

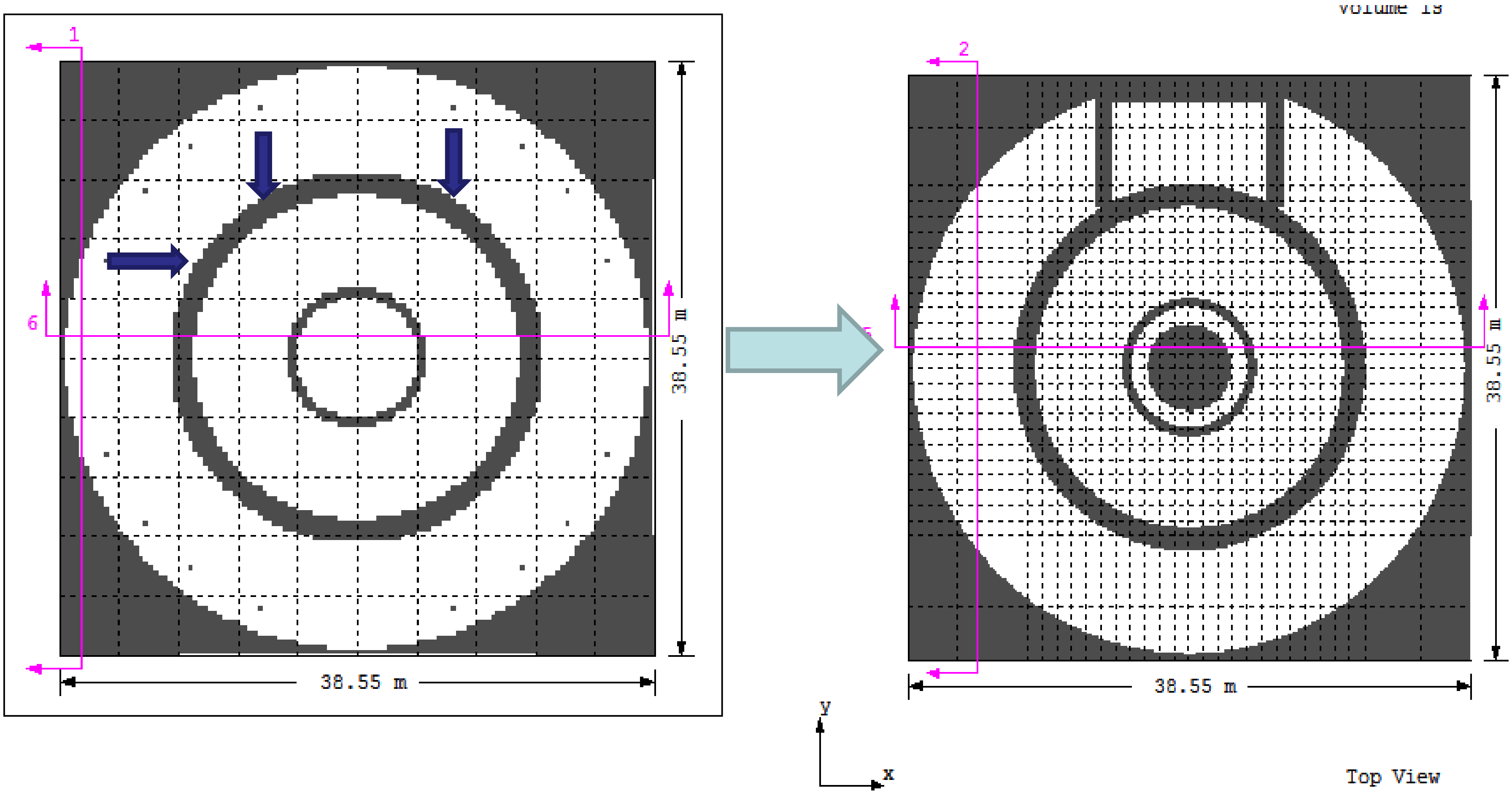
General approach to Containment Modelling



Detailed Model

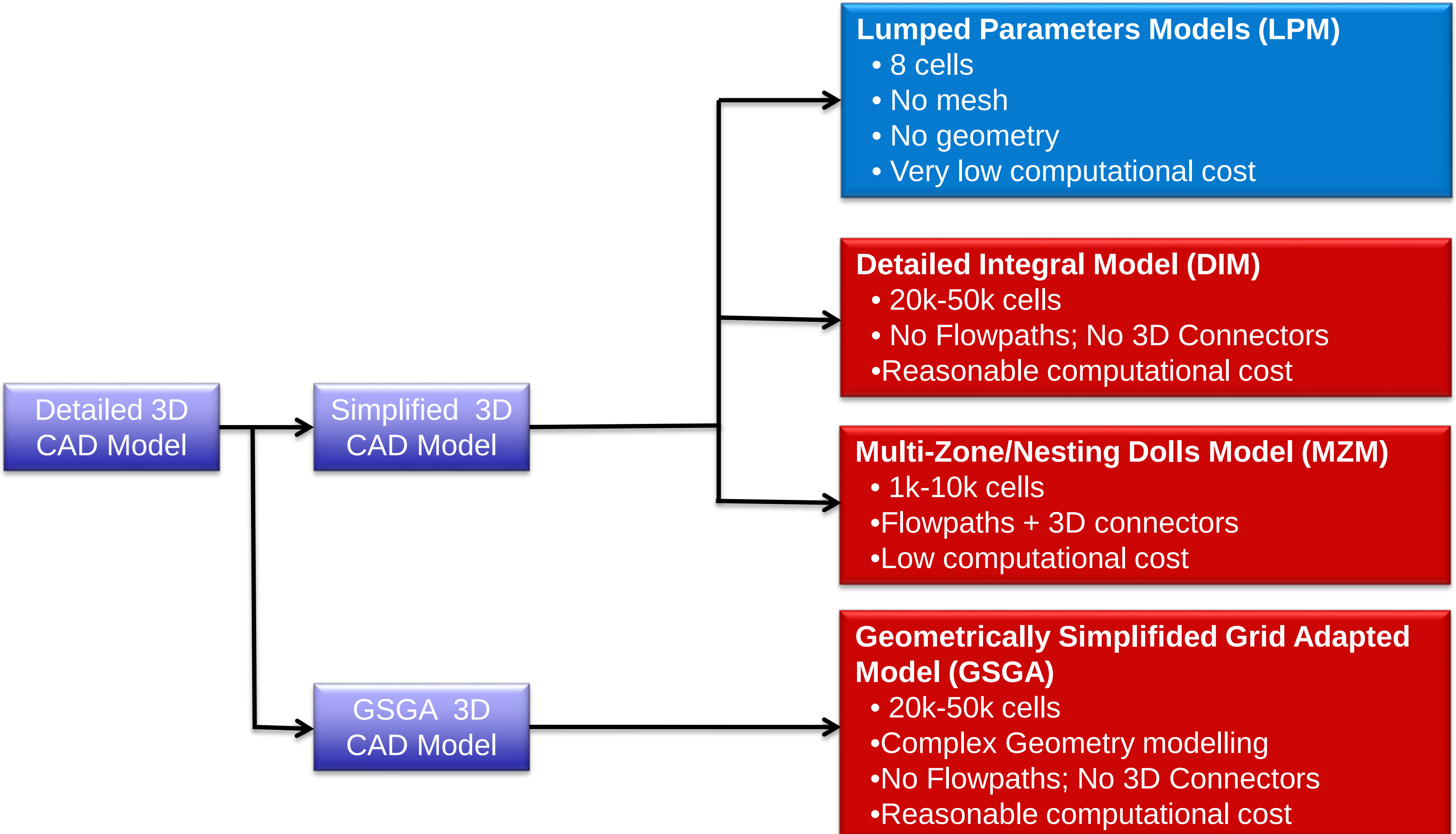
Simplified Geometries Model

General approach to Containment Modelling



A challenge of Porous CFDs is fluid separation between walls

General approach to Containment Modelling



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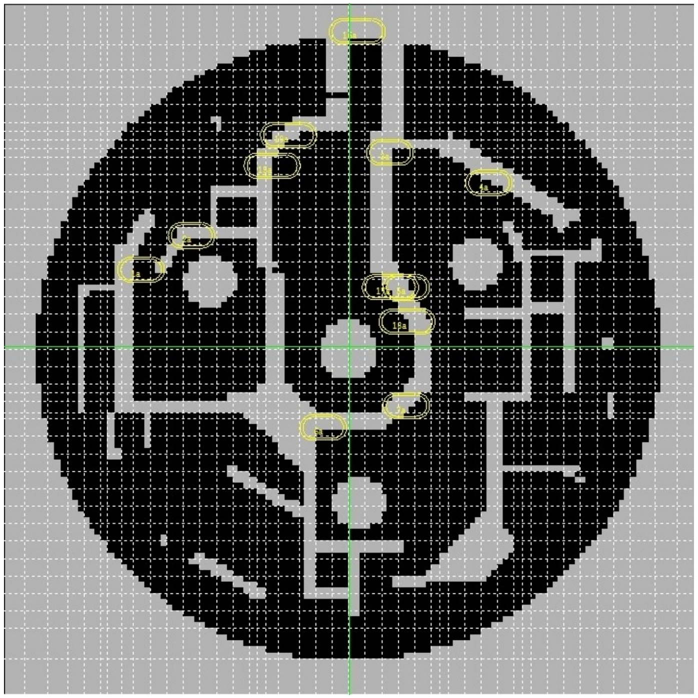
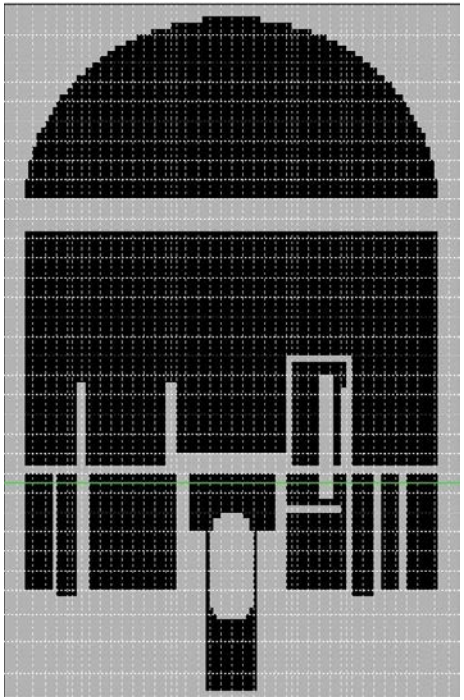
Detailed Integral Modelling

Integral model : Single Subdivided Volume



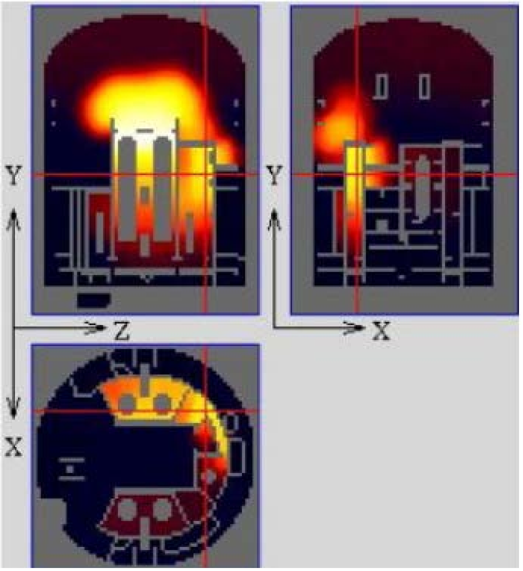


With simple geometries a fine mesh can capture fluid separation

Ref: Bocanegra, R., Jimenez, G., Fernández-Cosials, M.K., 2016. Development of a PWR-W GOTHIC 3D model for containment accident analysis. Annals of Nuclear Energy 87, 547–560. https://doi.org/10.1016/j.anucene.2015.10.022

Example of Integral Model

Computational validation of the EPR™ combustible gas control system.
Nuclear Engineering and Design 249 (2012) 118–124

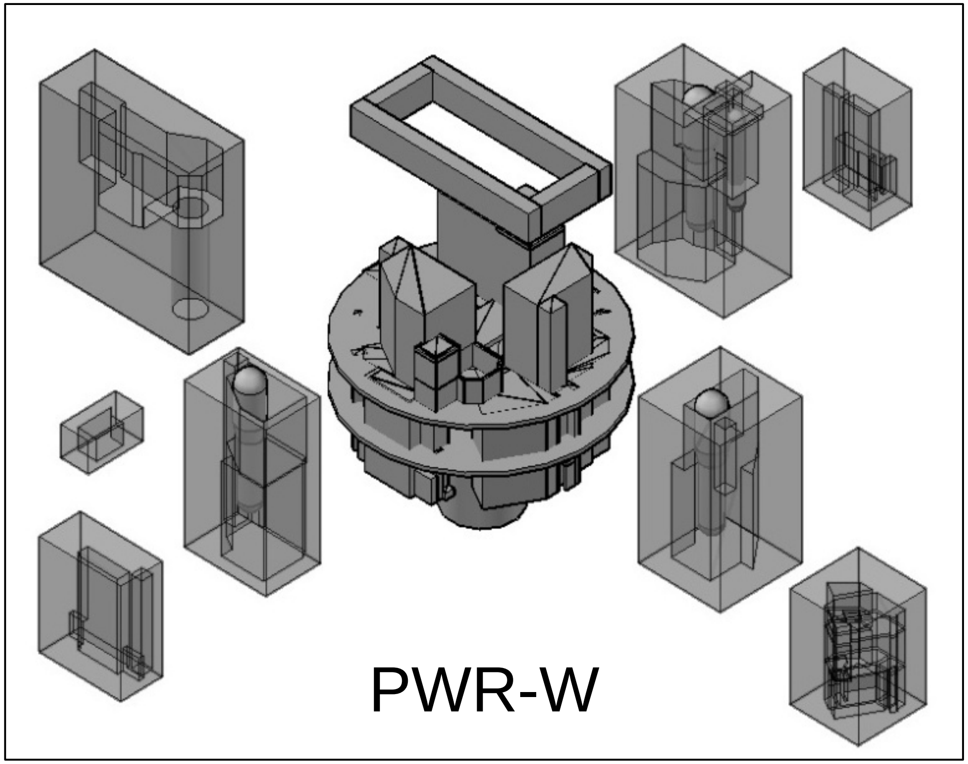


UK EPR™ features a total of 47 passive catalytic recombiners (41 large and 6 small) distributed throughout the containment

Nesting Dolls/Multi-zone approach

- It allows a coarse mesh reducing computational effort

- Reduces the detail and accuracy in exchange of more stability and less computational effort.



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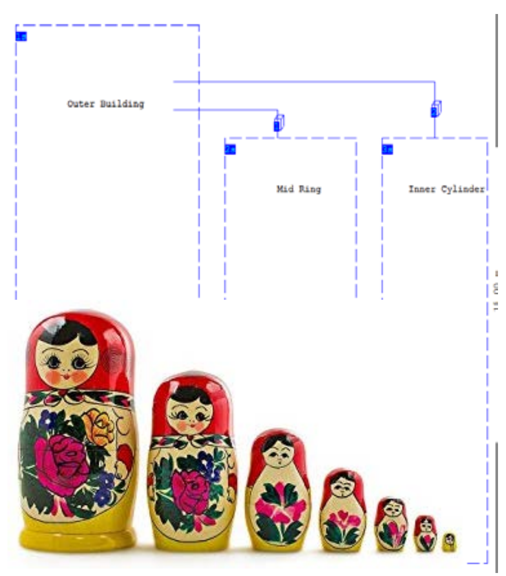
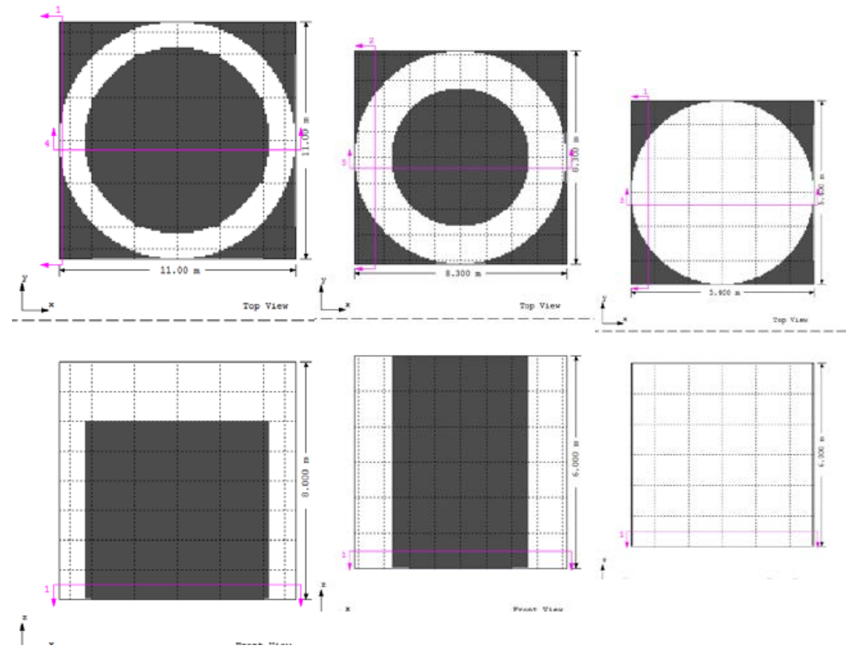
Nesting Dolls/Multi-zone approach

- Different Subdivided volumes to mantain fluid separation between walls



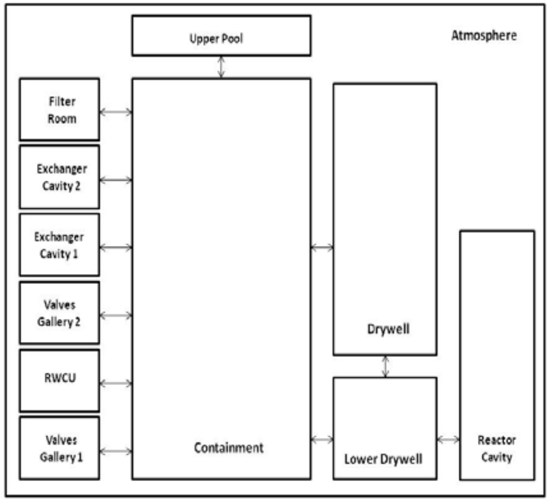


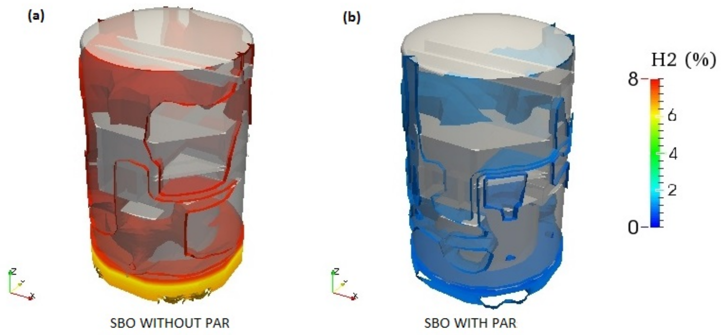
Used by UPM in BWR/Mark III, PWR-W and PWR-KWU containment models

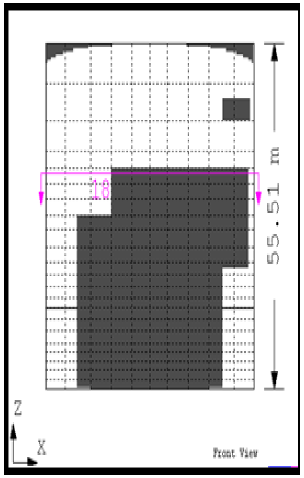
Ref: C. Serrano, et al.. A proposed methodology for the Passive Autocatalytic Recombiner sizing and location for a BWR Mark-III reactor containment building. Annals of Nuclear Energy 94 (2016) 589–602

Example of Nesting Dolls/Multi-zone approach

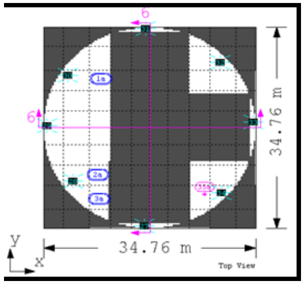
- With complex geometries an multi-zone approach is normally the best approach.







BWR-MarkIII



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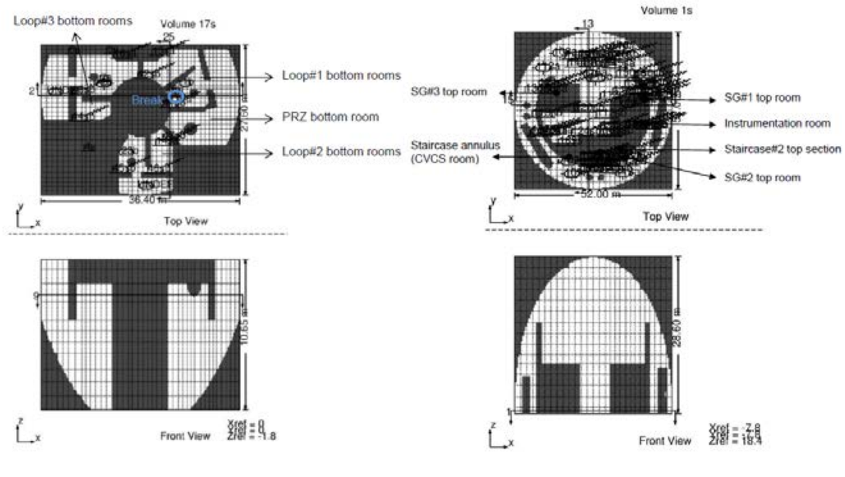


Figure 2: Nodalization detail for lower containment volume (Vol.17s) (a) and upper containment volume (Vol.1s) (b).

PWR-KWU

Ref: Simulation of the hydrogen distribution in a power plant using the GOTHIC code. D. Papini, P. Steiner, M. Andreani, B. Ničeno, J.-U. Klügel and H.-M. Prasser. ERMSAR2015 Marseille (France)

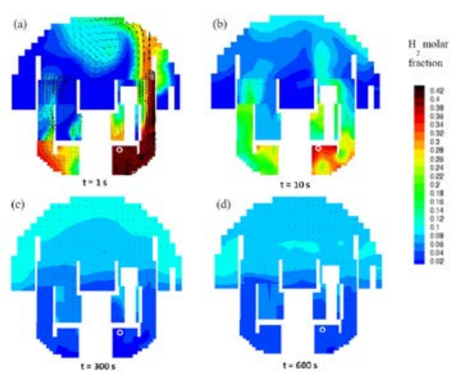


Figure 4: Contour maps of hydrogen distribution in time (vertical cut through the break location)

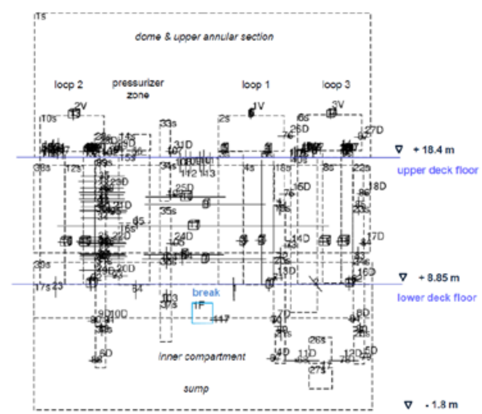
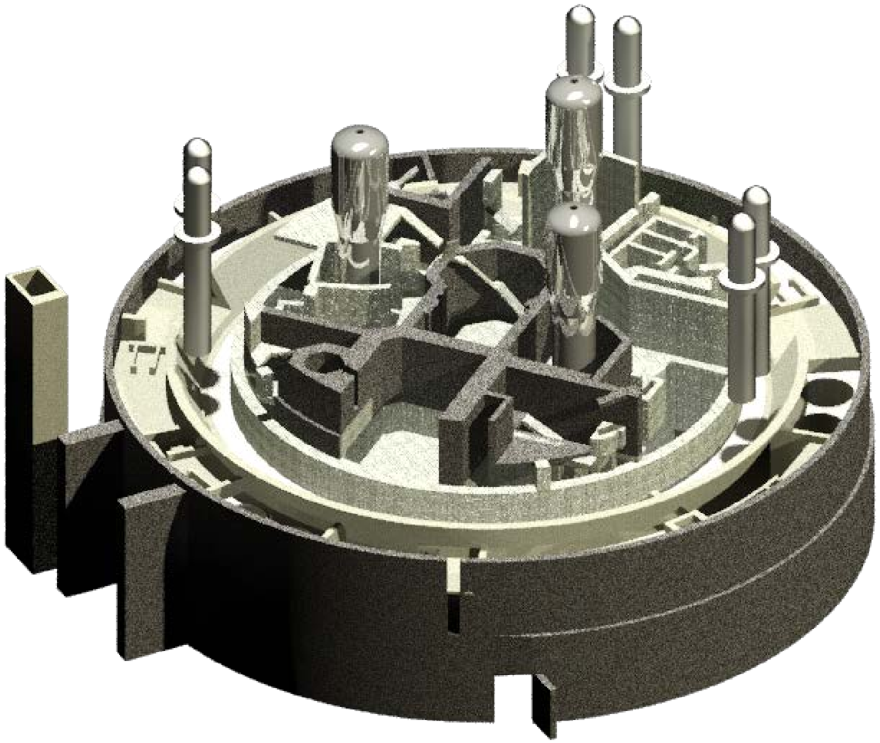


Figure 1: Containment nodalization diagram.

Geometrically Simplified Grid Adapted approach

- In order to create an integral model of a complex geometry the GSGA approach can be used.

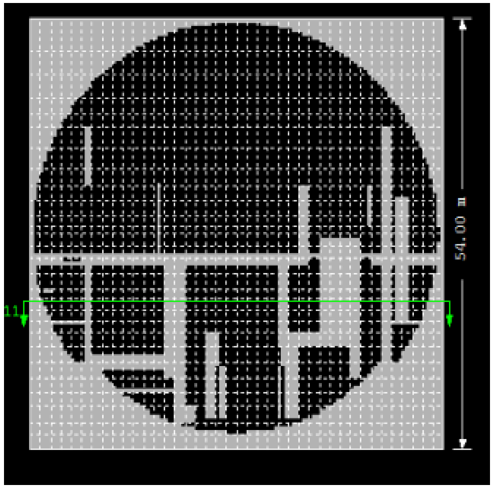
- This is the case of Trillo NPP (PWR-KWU)

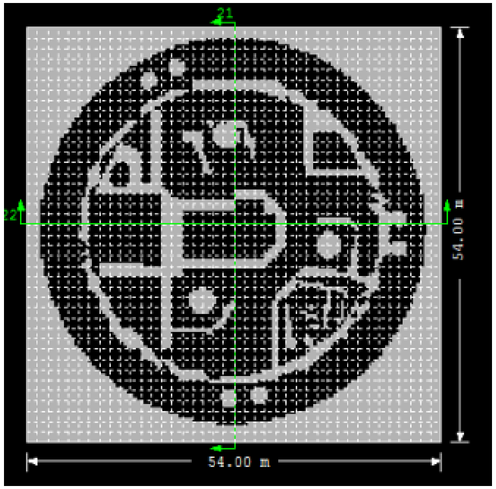


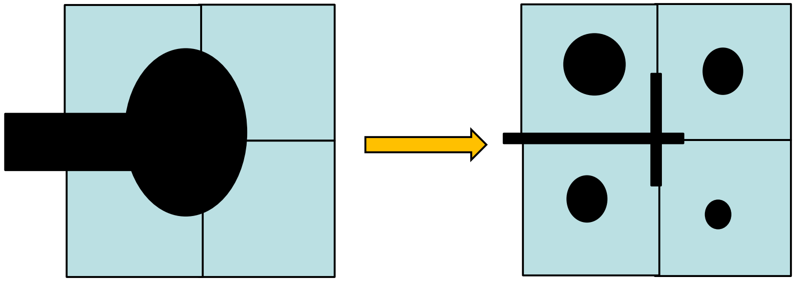
Ref: Fernández-Cosials et al. Desarrollo de un modelo 3D de contención de la Central Nuclear de Trillo mediante un proceso de modelización optimizado In Spanish Nuclear Society Annual Meeting 2018

Geometrically Simplified Grid Adapted approach

- The porous CFD does not “see” this geometry change.
- **Geometry is rebuilt** over a pre-established mesh
- The process is the “inverse” to CFD meshing.







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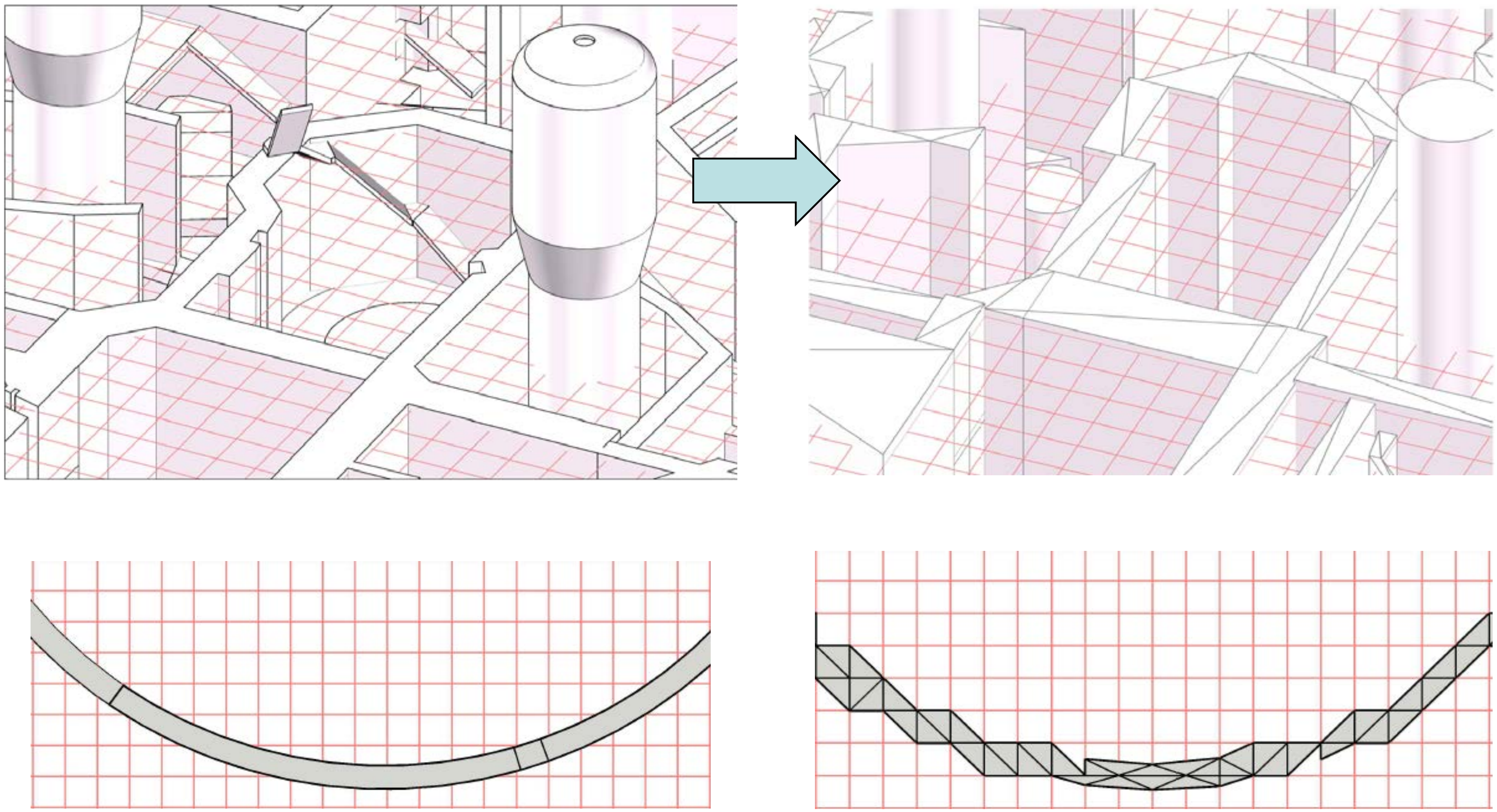
Geometrically Simplified Grid Adapted approach



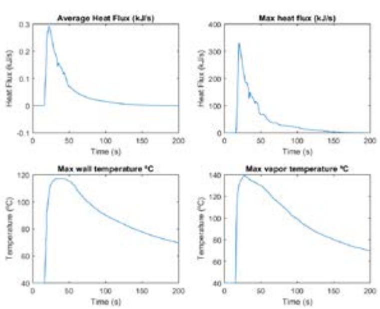
Detailed model

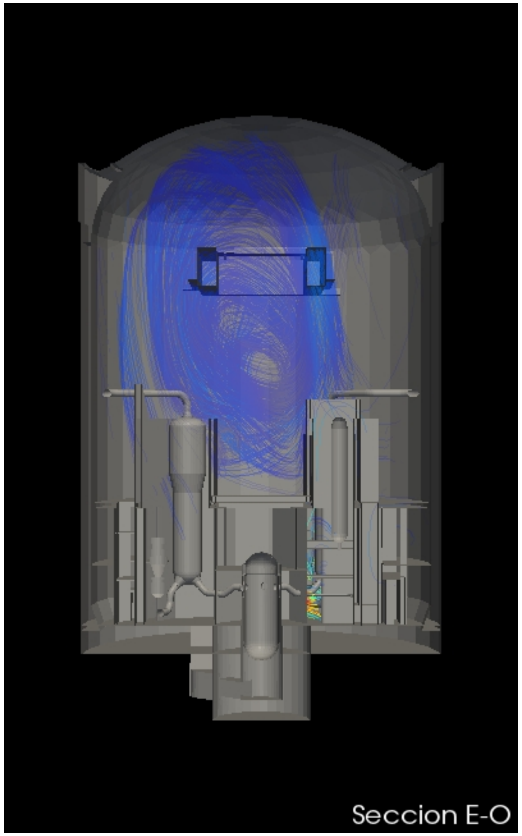
GSGA model

Add-ons to the methodology (bricklayers)

A series of Scripts, Programs and Add-ons are used to bound the different methdologies:

- Capability to analyze each room independently
- Capability to analyze flow patterns
- Capability to analyze hydrogen risk
- Matlab, Paraview, Python, dlls AutohotKeys...





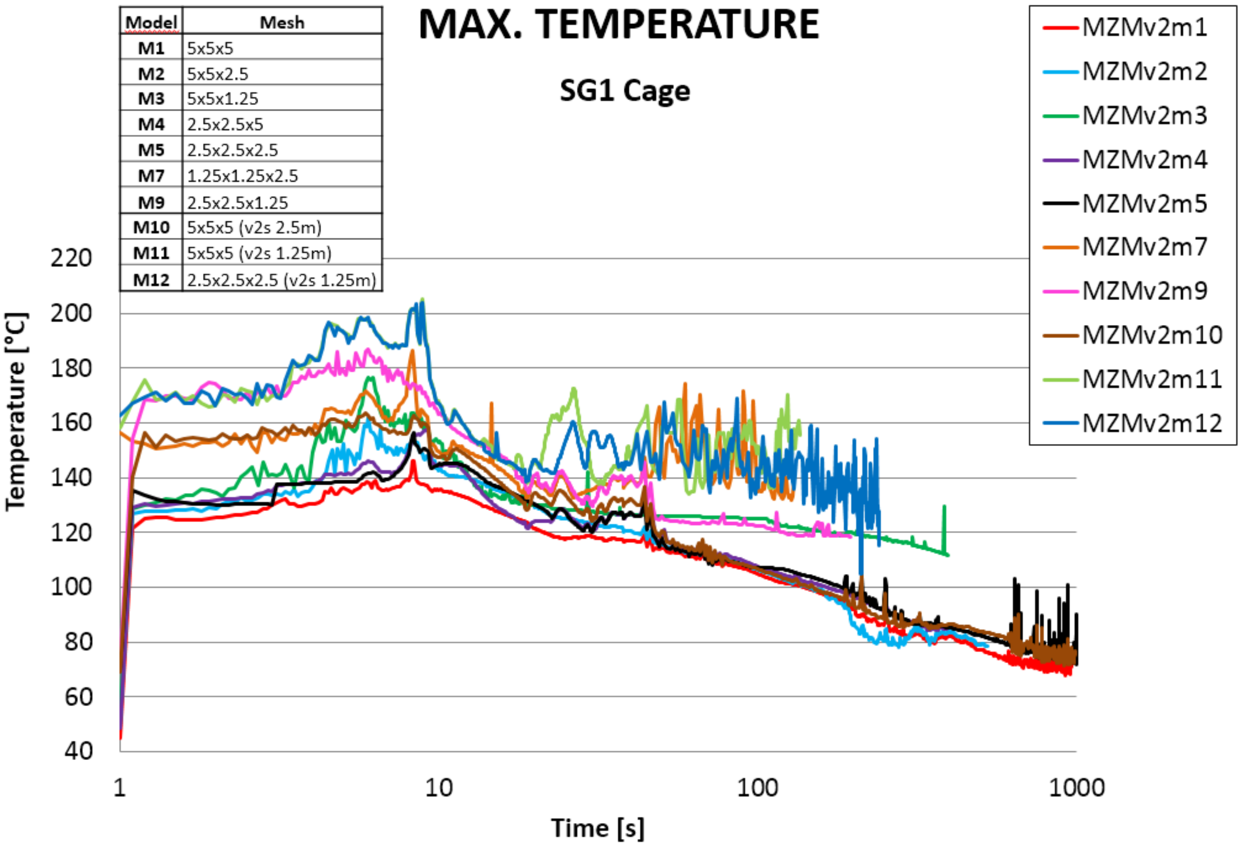
Applications of the GOTHIC code (pre-step)

"The frequently heard argument 'any solution is better than none' can be dangerous in the extreme. The greatest disaster one can encounter in computation is not instability or lack of convergence but results that are simultaneously good enough to be believable but bad enough to cause trouble."

\- *Ferziger & Peric*

Applications of the GOTHIC code (pre-step)

Model	Cell size	Aspect Ratio	Cell Num	CPU Time [h]
M1	5x5x5	1	1829	1.33
M2	5x5x2.5	2	3366	2.66
M3	5x5x1.25	4	6732	144.00
M4	2.5x2.5x5	2	7316	8.70
M5	2.5x2.5x2.5	1	13464	6.81
M6	1.25x1.25x5	4	29264	178.09
M7	1.25x1.25x2.5	2	60336	107.61
M8	1.25x1.25x1.25	1	107712	215.30
M9	2.5x2.5x1.25	2	26928	144.00
M10	5x5x5 (v2s 2.5m)	2	2321	11.45
M11	5x5x5 (v2s 1.25m)	4	6353	5.25
M12	2.5x2.5x2.5 (v2s 1.25m)	2	17496	85.00



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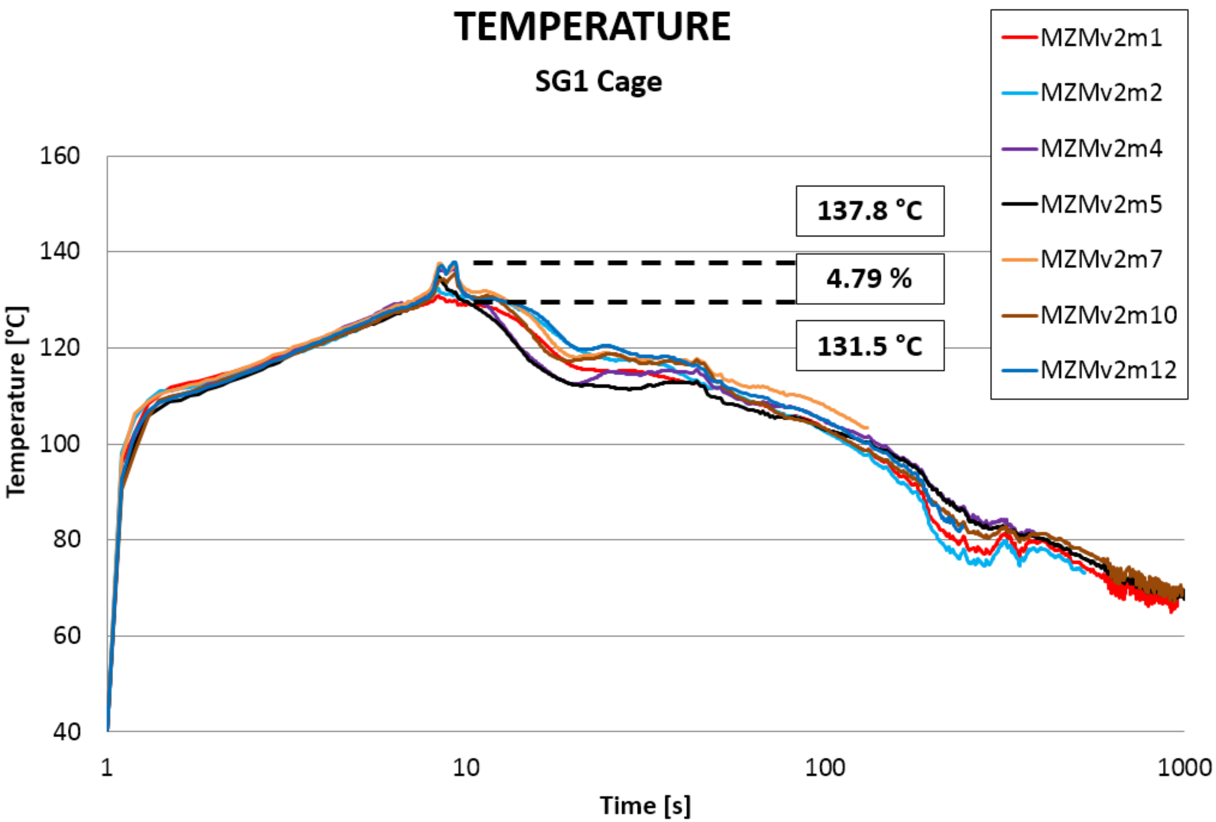

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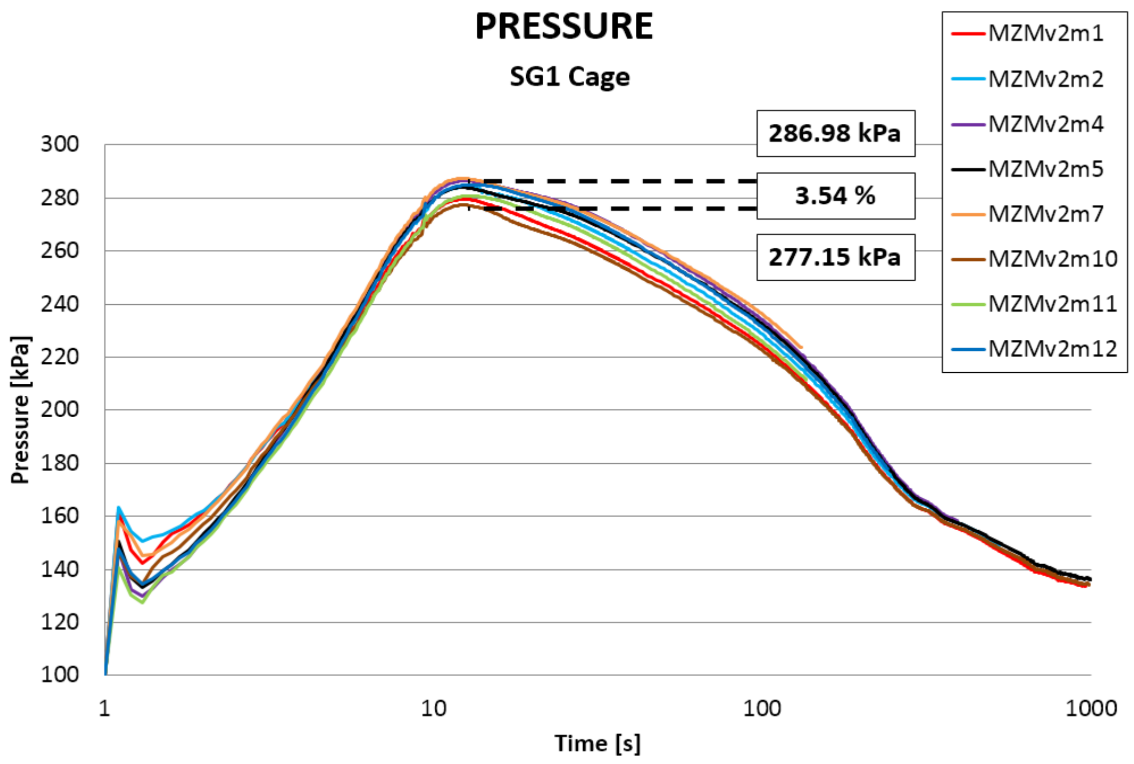
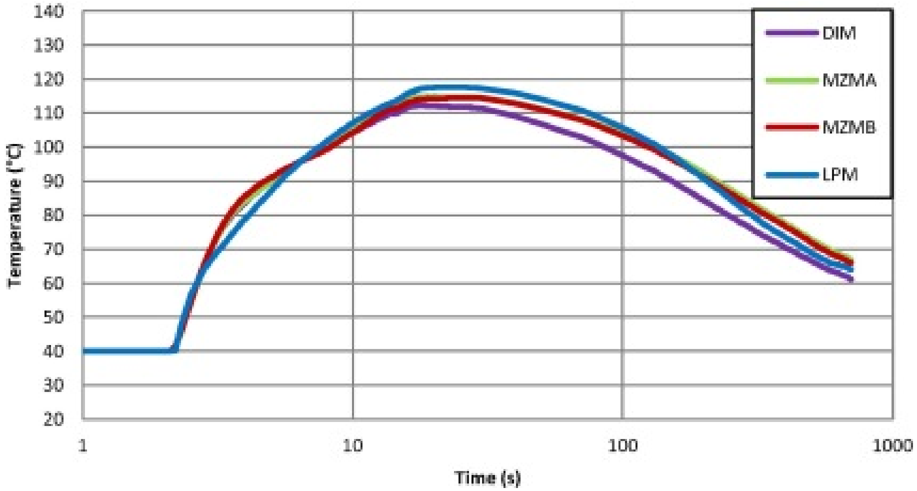
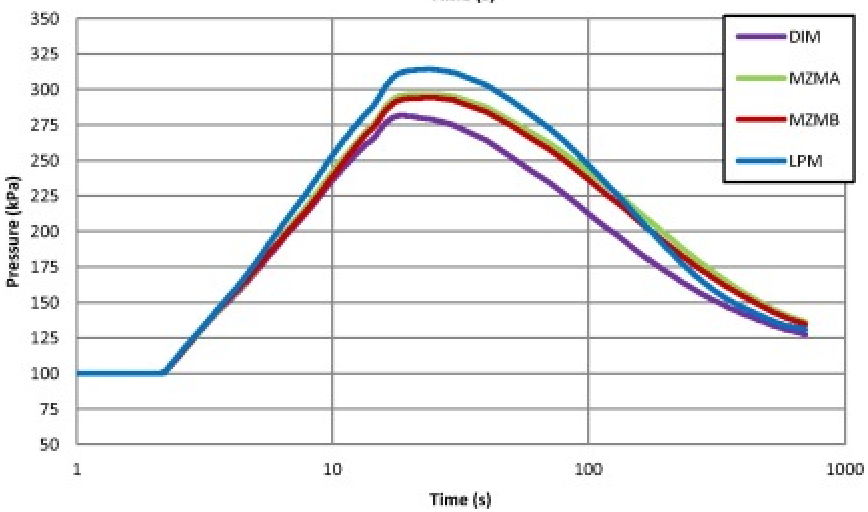


Applications of the GOTHIC code (pre-step)

- The comparison of average values between Lumped Parameters models and 3D show similar trends
- The condensation and heat transfer affect the different values.





Modeling Conclusions GOTHIC

- It is possible to build a 3D detailed model with the GOTHIC code with reasonable computational cost.
- The results of the simulations are in agreement with other comparable lumped parameters simulations for LBLOCA in the containment building.
- The 3D models developed allow studying the behavior of all the containment rooms and regions during an accident.
- Use of the Integral/GSGA to obtain local maximum temperatures in a LOCA/MSLB transient & Use of the Multi-Zone/Nesting Dolls to reduce computational cost for a sensitivity analysis

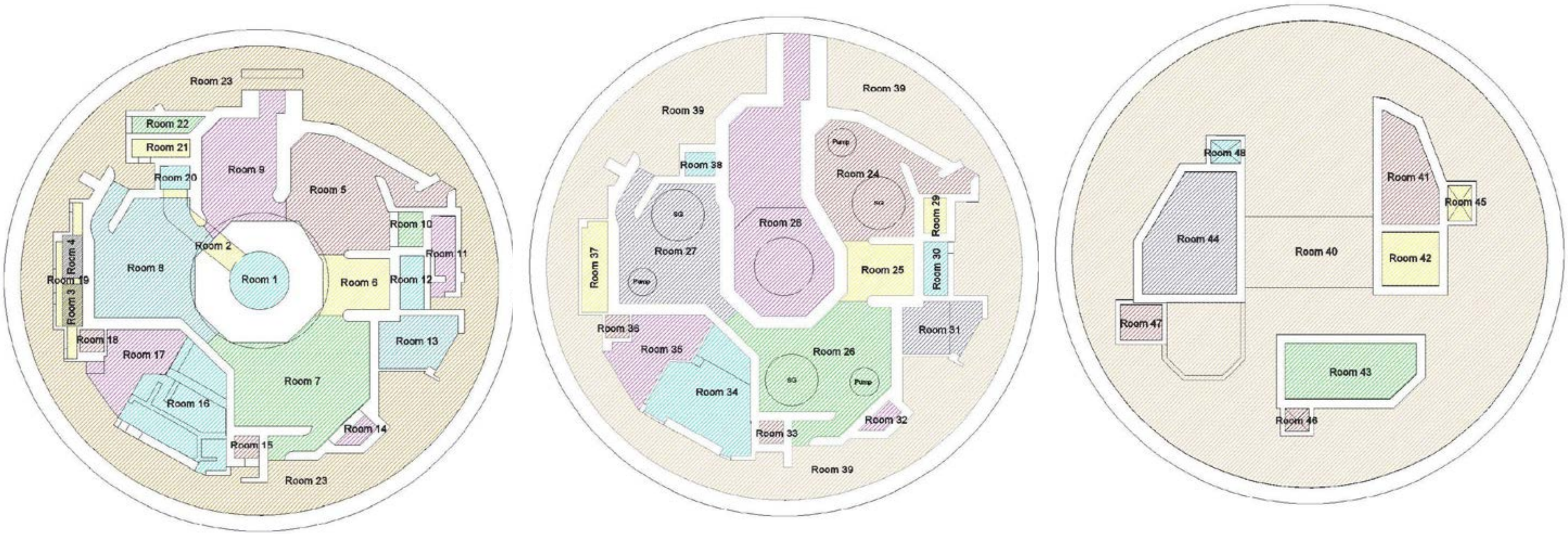
Applications of the GOTHIC code

3D Containment Applications with GOTHIC in the UPM:

1. Analysis of Equipment and instrumentation Qualification Criteria
2. Analysis of Venting Strategy and hydrogen risk
3. Methodology for location and analysis of Passive Autocatalytic Recombiners
4. Simulation of AP1000 Mass and Energy Release in Containment

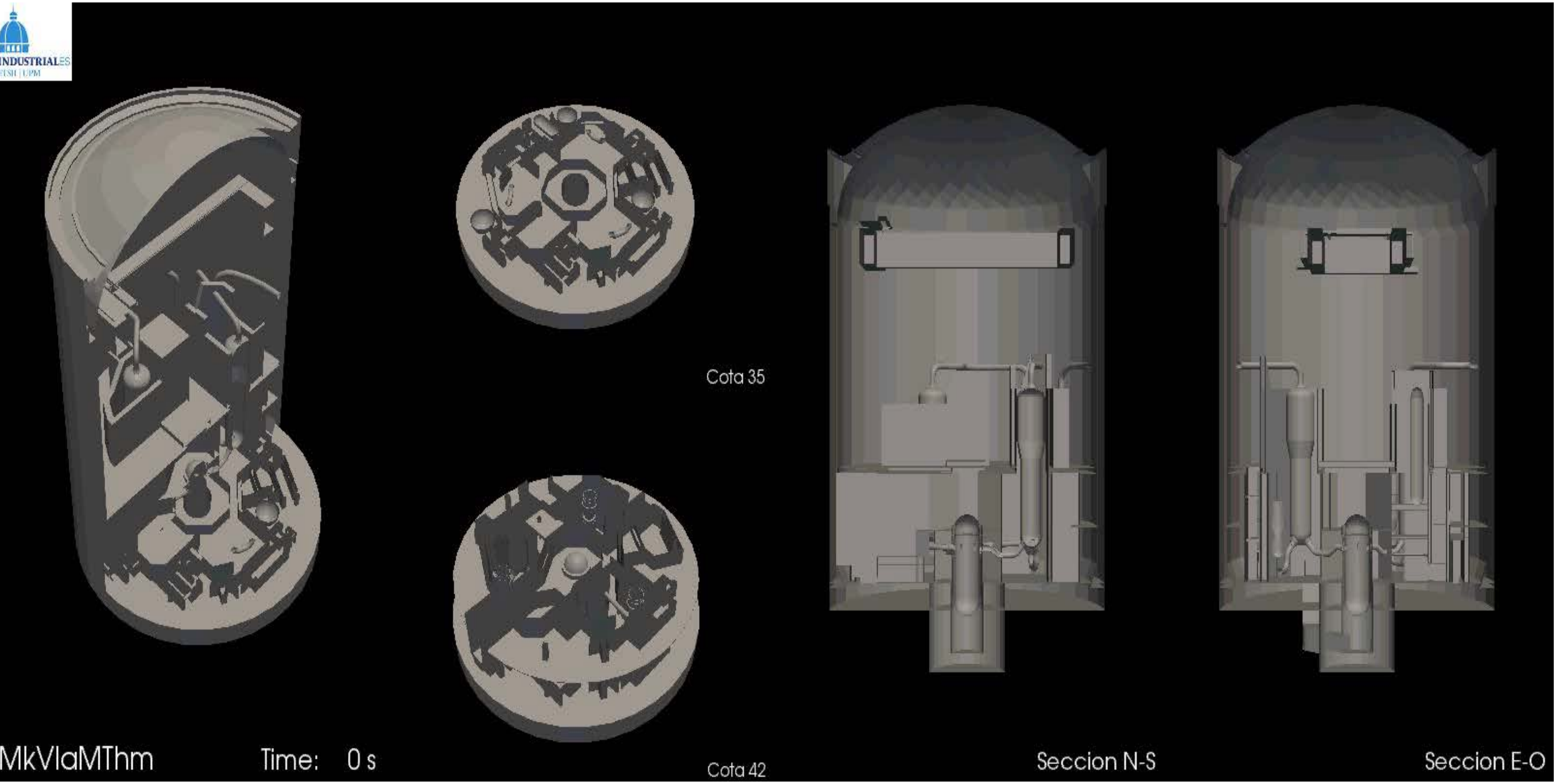
1. Analysis of Equipment and instrumentation Qualification Criteria

Use of the **Detailed Integral** PWR-W model to run detailed simulations.



Containment divided into 49 Different Rooms

1. Analysis of Equipment and instrumentation Qualification Criteria



Ref: Analysis of the equipment and instrumentation qualification criteria using 3D containment models. G. Jimenez, K. Fernandez-Cosials, R. Bocanegra, C. Queral. Nuclear Engineering and Design 323 (2017) 28–38

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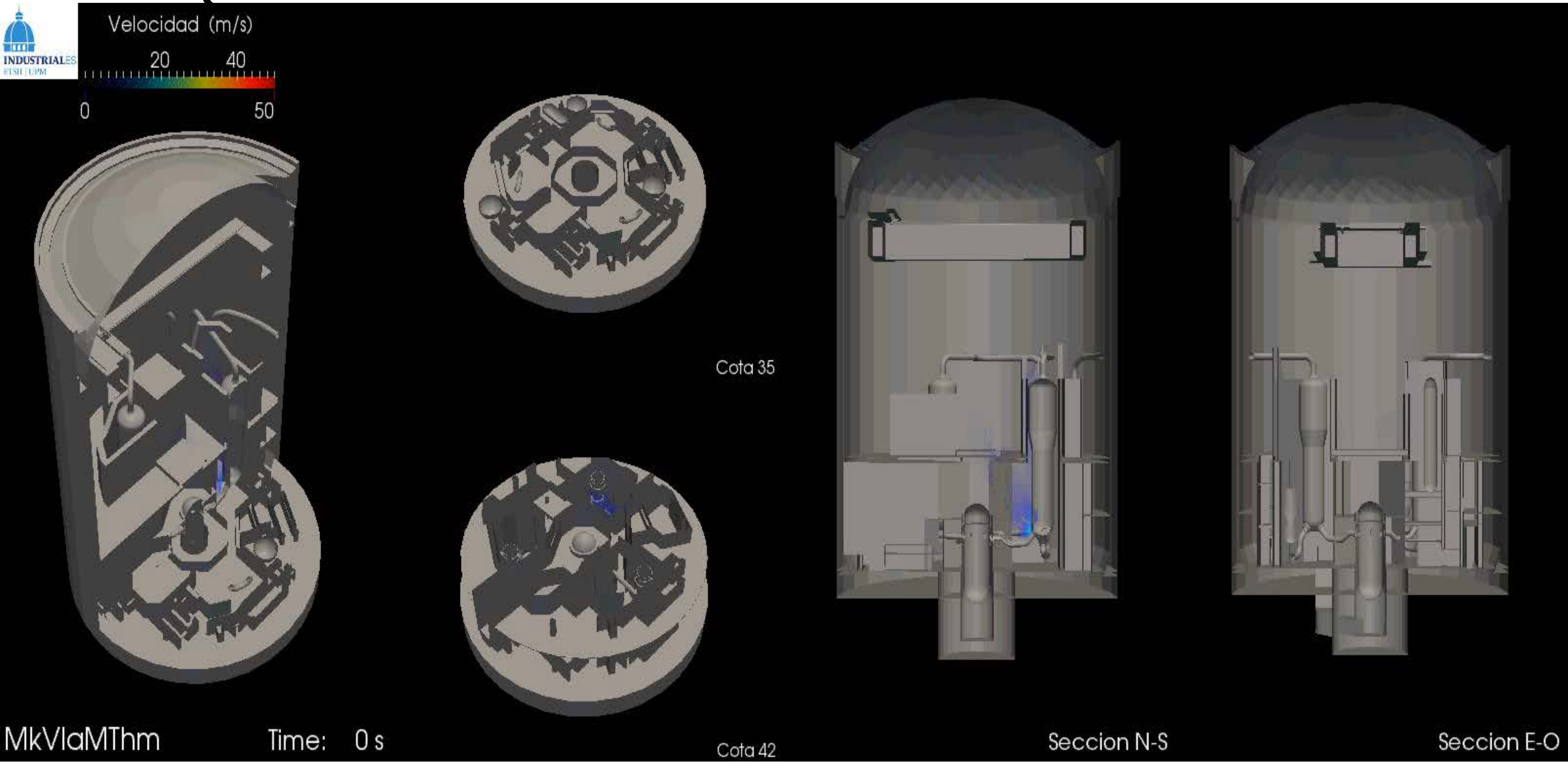

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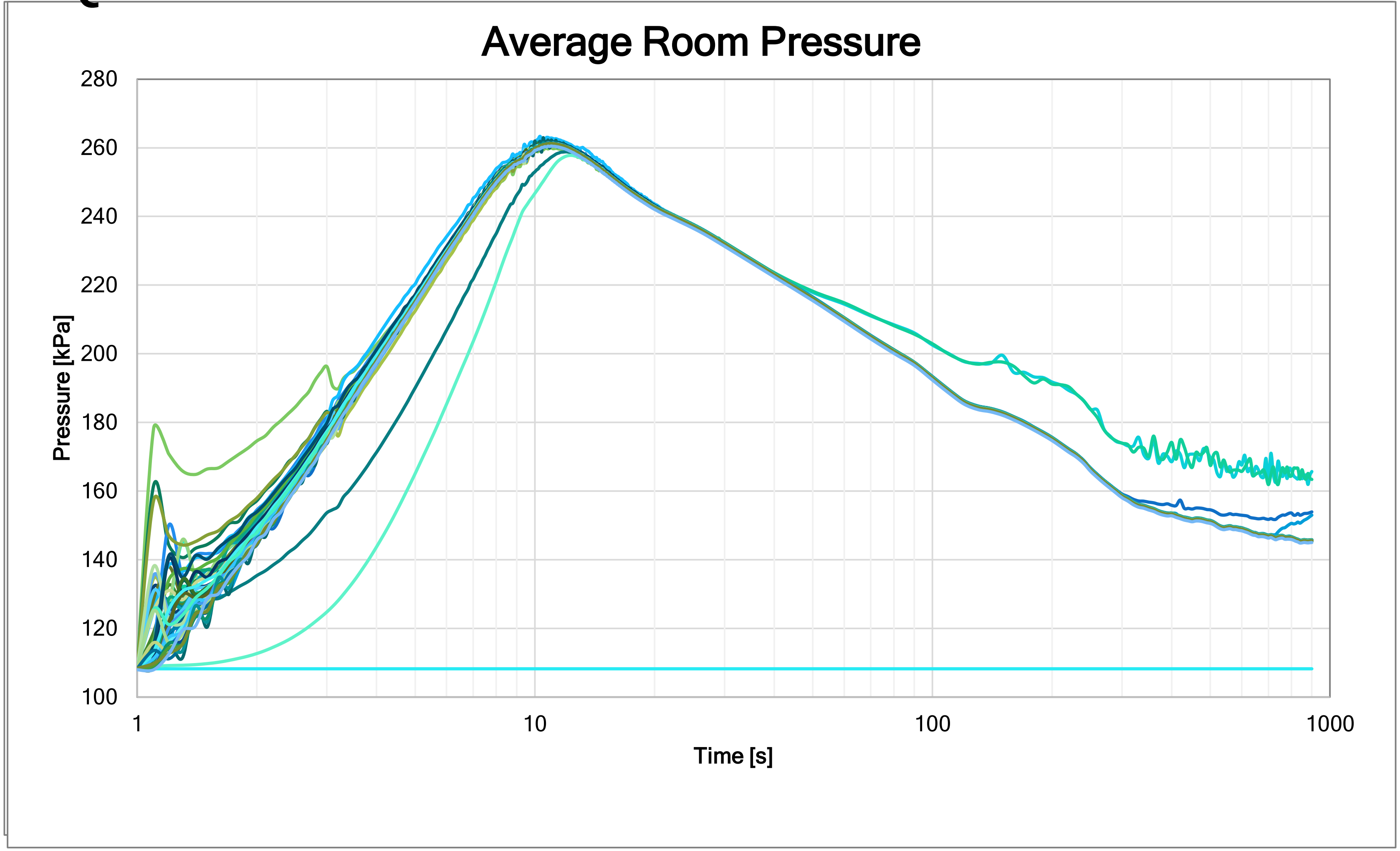

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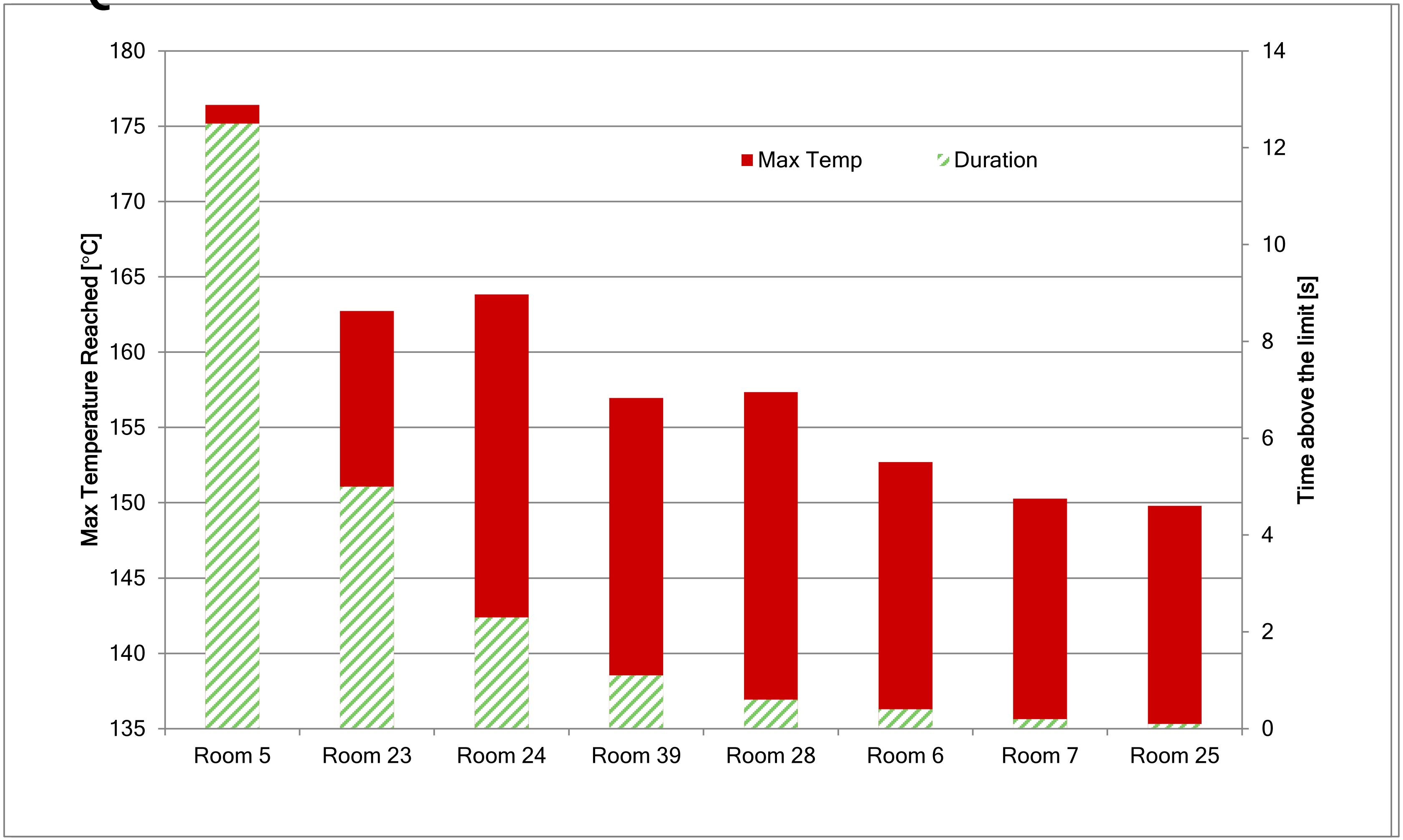
1. Analysis of Equipment and instrumentation Qualification Criteria



Ref: Analysis of the equipment and instrumentation qualification criteria using 3D containment models. G. Jimenez, K. Fernandez-Cosials, R. Bocanegra, C. Queral. Nuclear Engineering and Design 323 (2017) 28–38

1. Analysis of Equipment and instrumentation Qualification Criteria

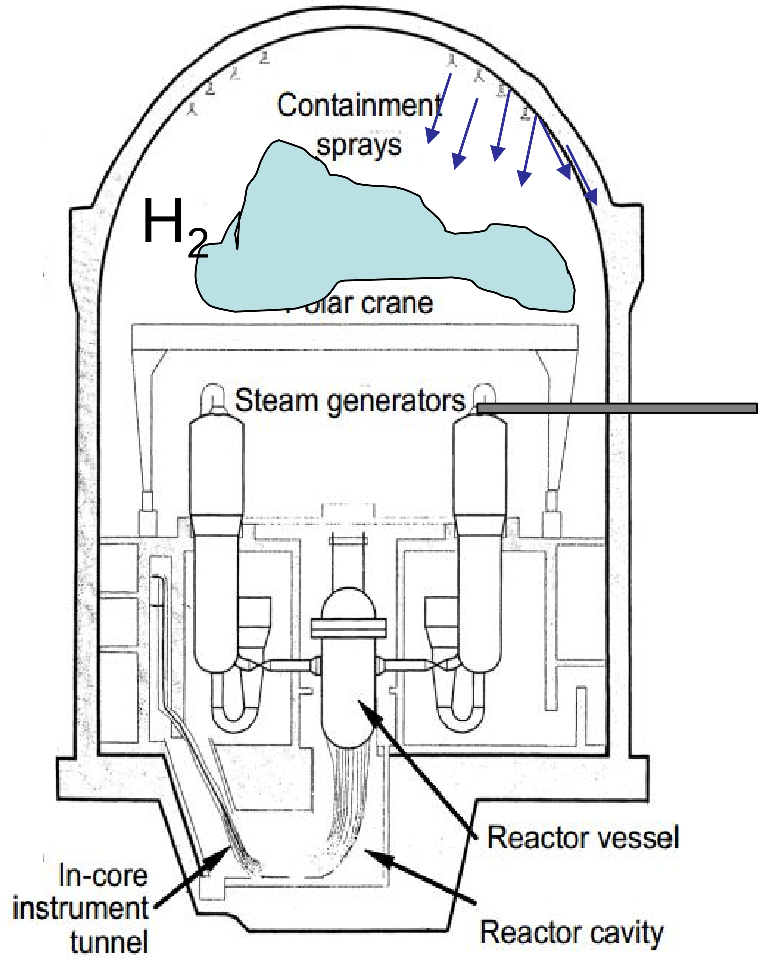
From the results obtained, a proposal was raised: 3D models should be used to evaluate the potential damage for the containment equipment and instrumentation during an accident.

Ref: Analysis of the equipment and instrumentation qualification criteria using 3D containment models. G. Jimenez, K. Fernandez-Cosials, R. Bocanegra, C. Queral. Nuclear Engineering and Design 323 (2017) 28–38

2. Analysis of Venting Strategy and hydrogen risk

Particullary Interesting regarding Hydrogen danger

Hydrogen Mass ↓	Hydrogen Concentration ↑
Oxygen Mass ↓	Oxygen Concentration ↑



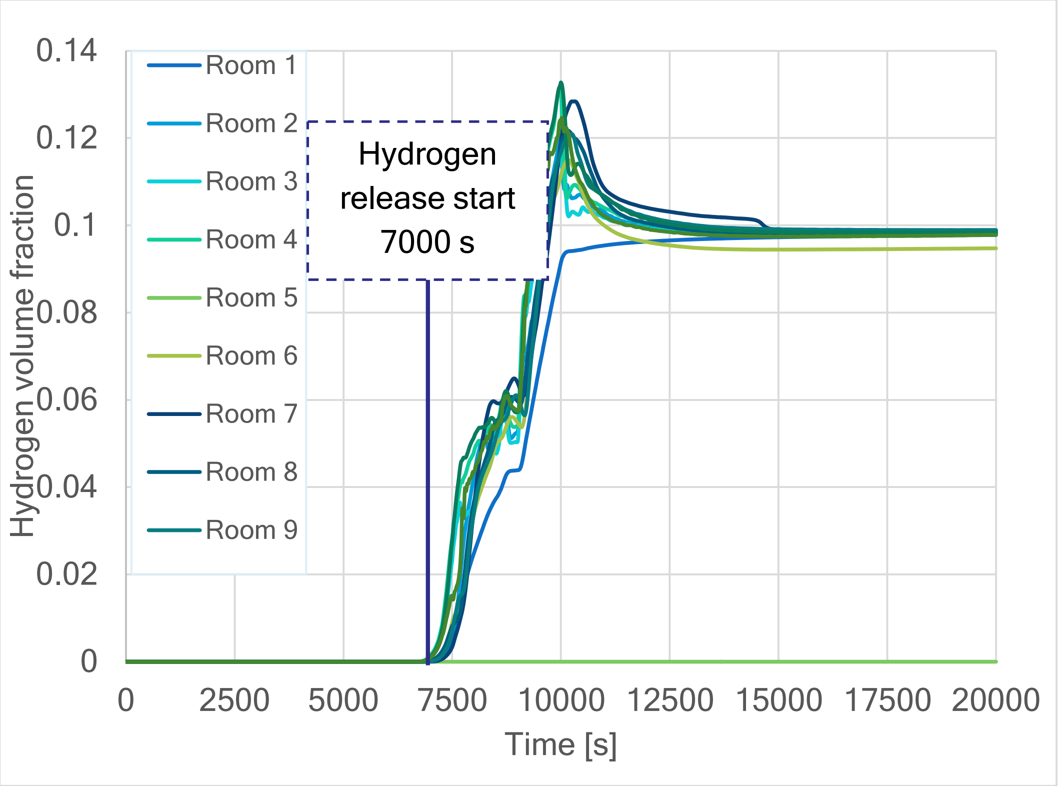
Venting and spray time and duration modifies H2 risk

Ref: Study of hydrogen risk in a PWR-W containment during a SBO scenario; Tau parameter definition and application on venting strategy analysis. Kevin Fernández-Cosials et al. Engineering and Design 325 (2017) 164–177

2. Analysis of Venting Strategy and hydrogen risk

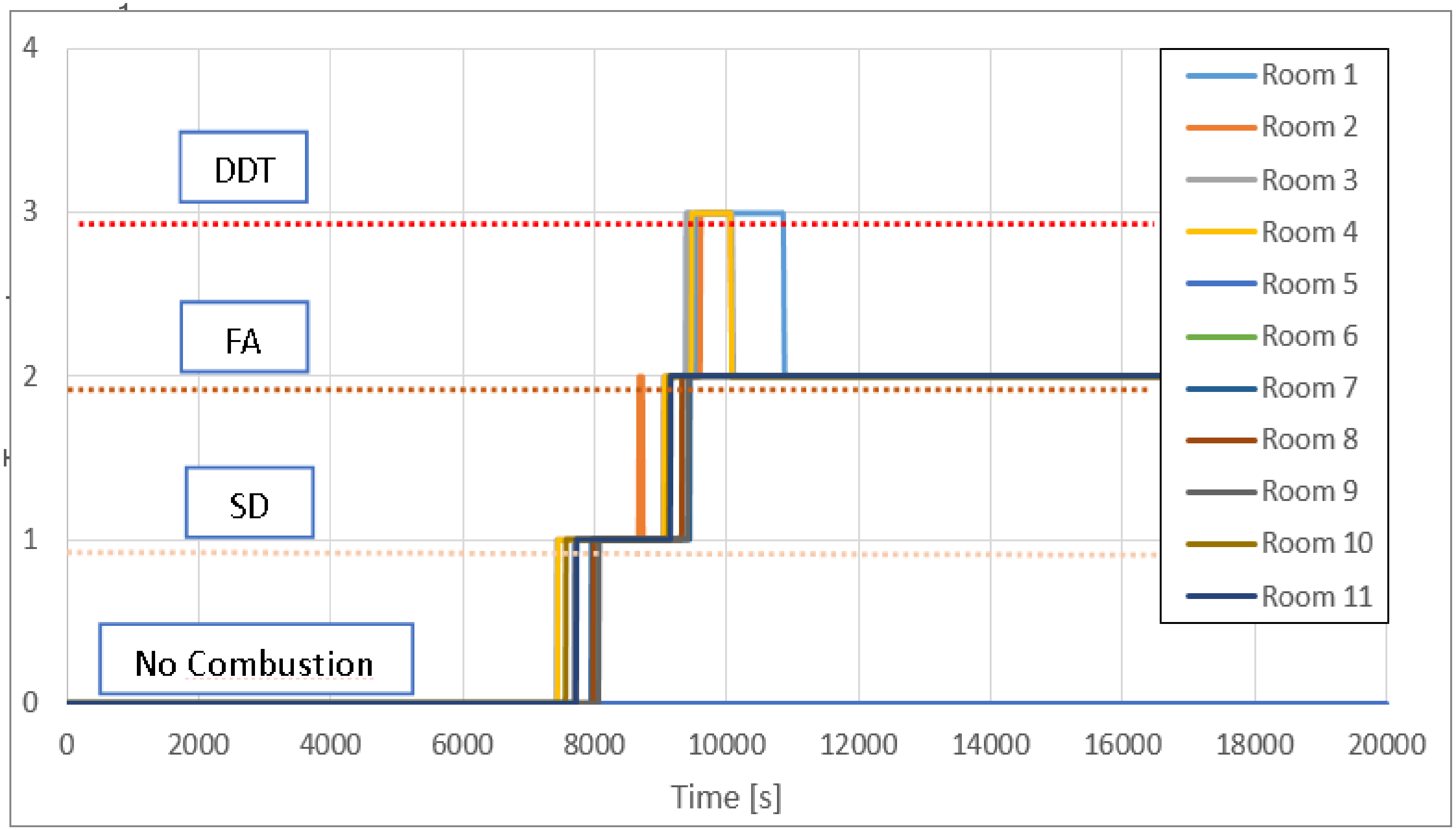
- Use of a PWR-W **Multi-zone model** to run dozens of simulations with an adequate accuracy.

- The sequence is an SBO that maximizes the hydrogen generation.

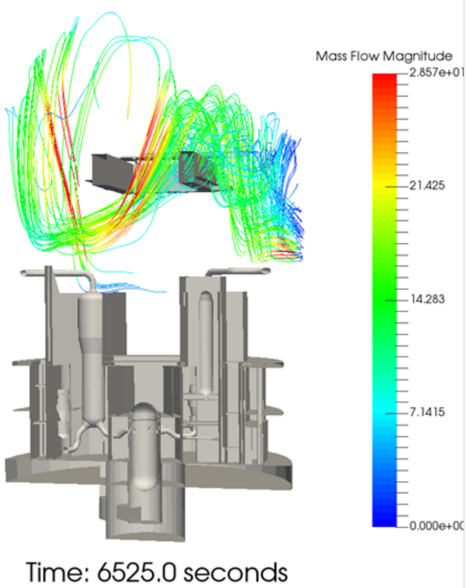


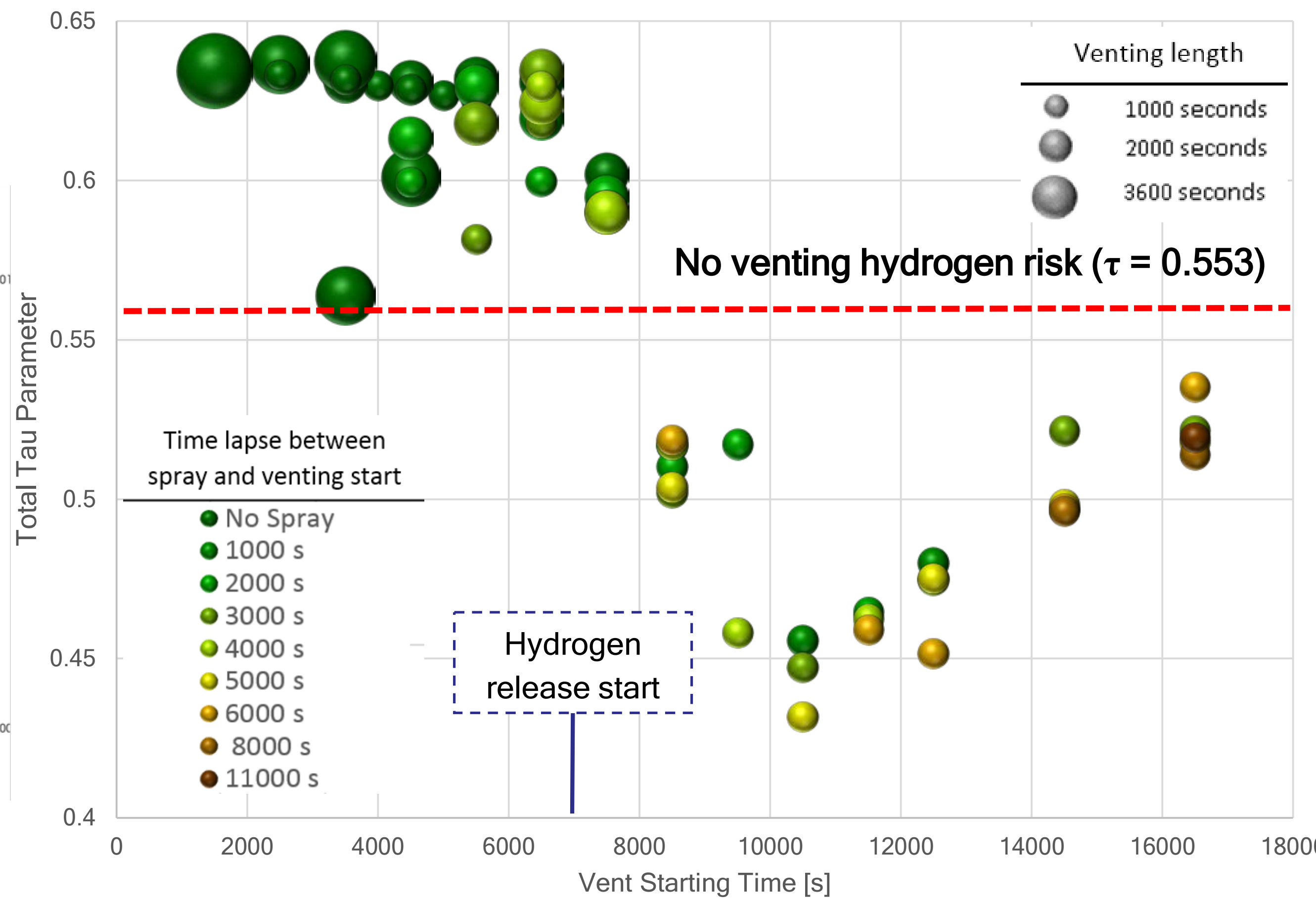
Ref: Study of hydrogen risk in a PWR-W containment during a SBO scenario; Tau parameter definition and application on venting strategy analysis. Kevin Fernández-Cosials et al. Engineering and Design 325 (2017) 164–177

2. Analysis of Venting Strategy and hydrogen risk



2. Analysis of Venting Strategy and hydrogen risk





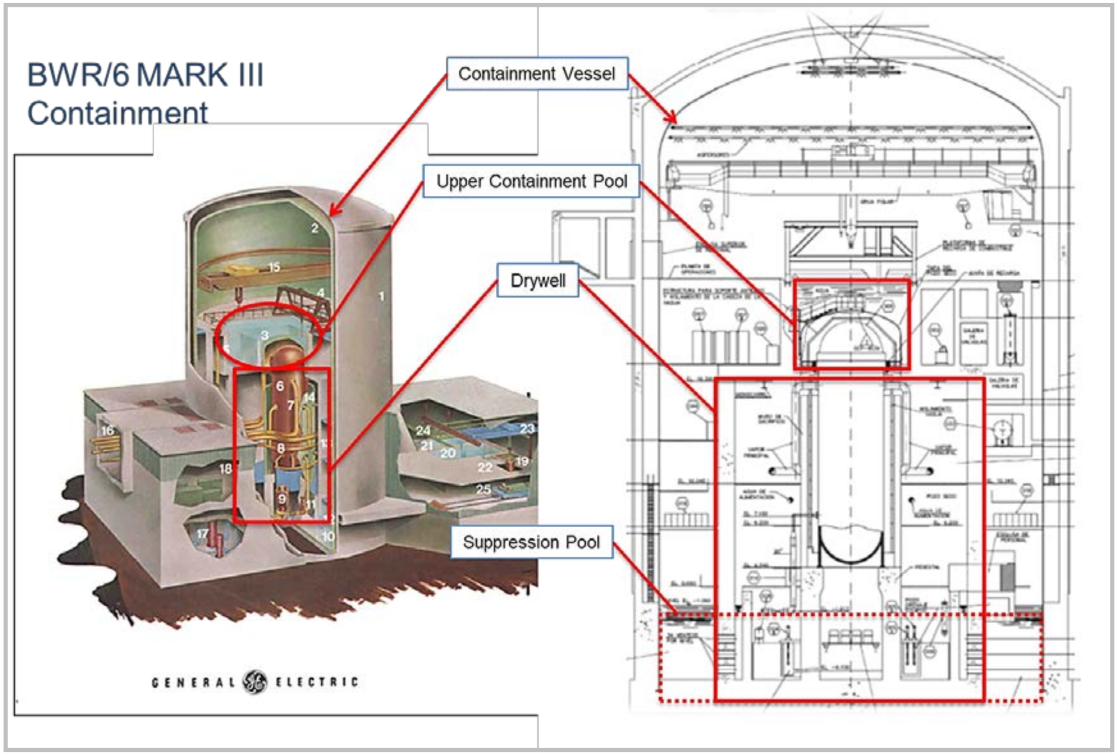
2. Analysis of Venting Strategy and hydrogen risk

From the results obtained, a temporal window to reduce the hydrogen risk was detected. Future applications of hydrogen risk quantification and assessment of SAMGs is projected

Ref: Study of hydrogen risk in a PWR-W containment during a SBO scenario; Tau parameter definition and application on venting strategy analysis. Kevin Fernández-Cosials et al. Engineering and Design 325 (2017) 164–177

3. Methodology for location and analysis of Passive Autocatalytic Recombiners

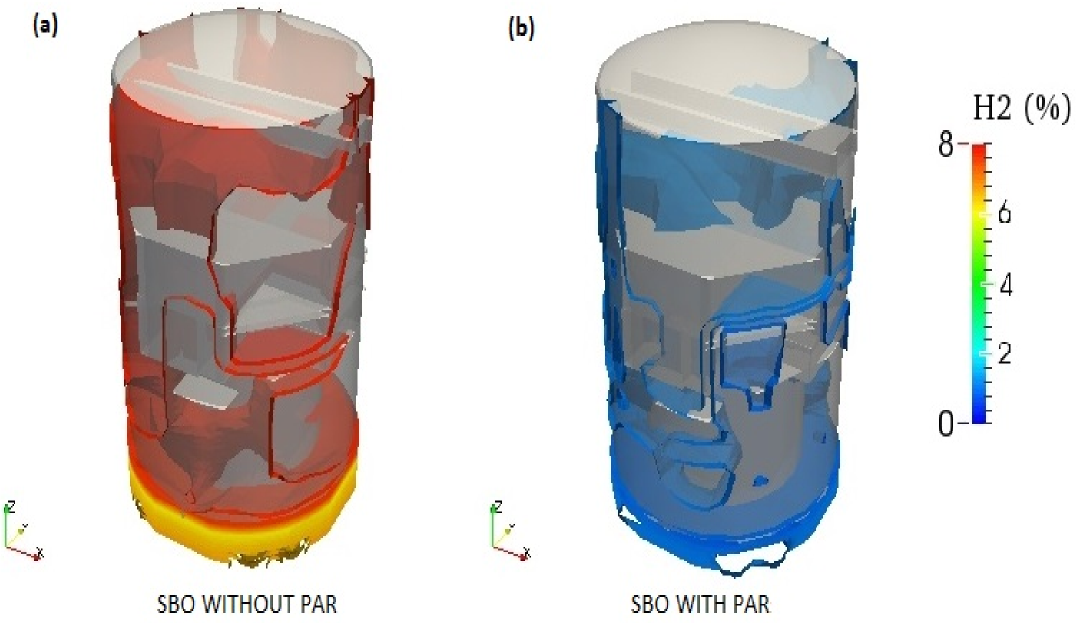
- The location and sizing of passive Autocatalitic Recombiners is a critical parameter to mitigate a Severe Accident
- Recombination of hydrogen into water
- Reduces the risk of hydrogen detonation which can impair the containment



Ref: C. Serrano, et al.. A proposed methodology for the Passive Autocatalytic Recombiner sizing and location for a BWR Mark-III reactor containment building. Annals of Nuclear Energy 94 (2016) 589–602

3. Methodology for location and analysis of Passive Autocatalytic Recombiners

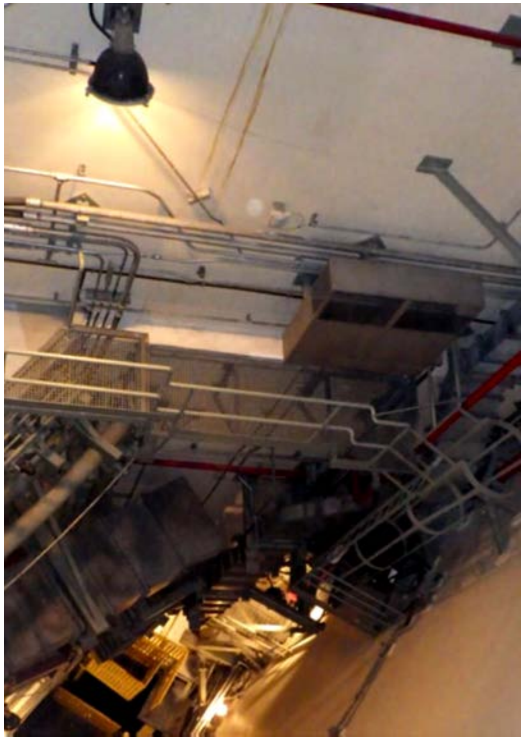
- The **Nesting-Dolls** model is used to simulate the accident.
- Algorithm that modifies PAR location and sizing and runs the simulation again.
- The PARs prevented the entrance into hazardous combustion regimes



Ref: C. Serrano, et al.. A proposed methodology for the Passive Autocatalytic Recombiner sizing and location for a BWR Mark-III reactor containment building. Annals of Nuclear Energy 94 (2016) 589–602

3. Methodology for location and analysis of Passive Autocatalytic Recombiners

- The **GOTHIC** code and the method used provided the location and sizing of the PARs of Cofrentes NPP.
- More than 40 PARs were installed in the DryWell, WetWell, Supression Pool …



PAR installation in Cofrentes NPP

Implantación de los Recombinadores Autocatalíticos Pasivos en la Central Nuclear de Cofrentes. C. Serrano, M. González, V. Zuriaga. Nuclear España, 381 (Febrero 2017), 39-42

Ref: C. Serrano, et al.. A proposed methodology for the Passive Autocatalytic Recombiner sizing and location for a BWR Mark-III reactor containment building. Annals of Nuclear Energy 94 (2016) 589–602

3. Methodology for location and analysis of Passive Autocatalytic Recombiners

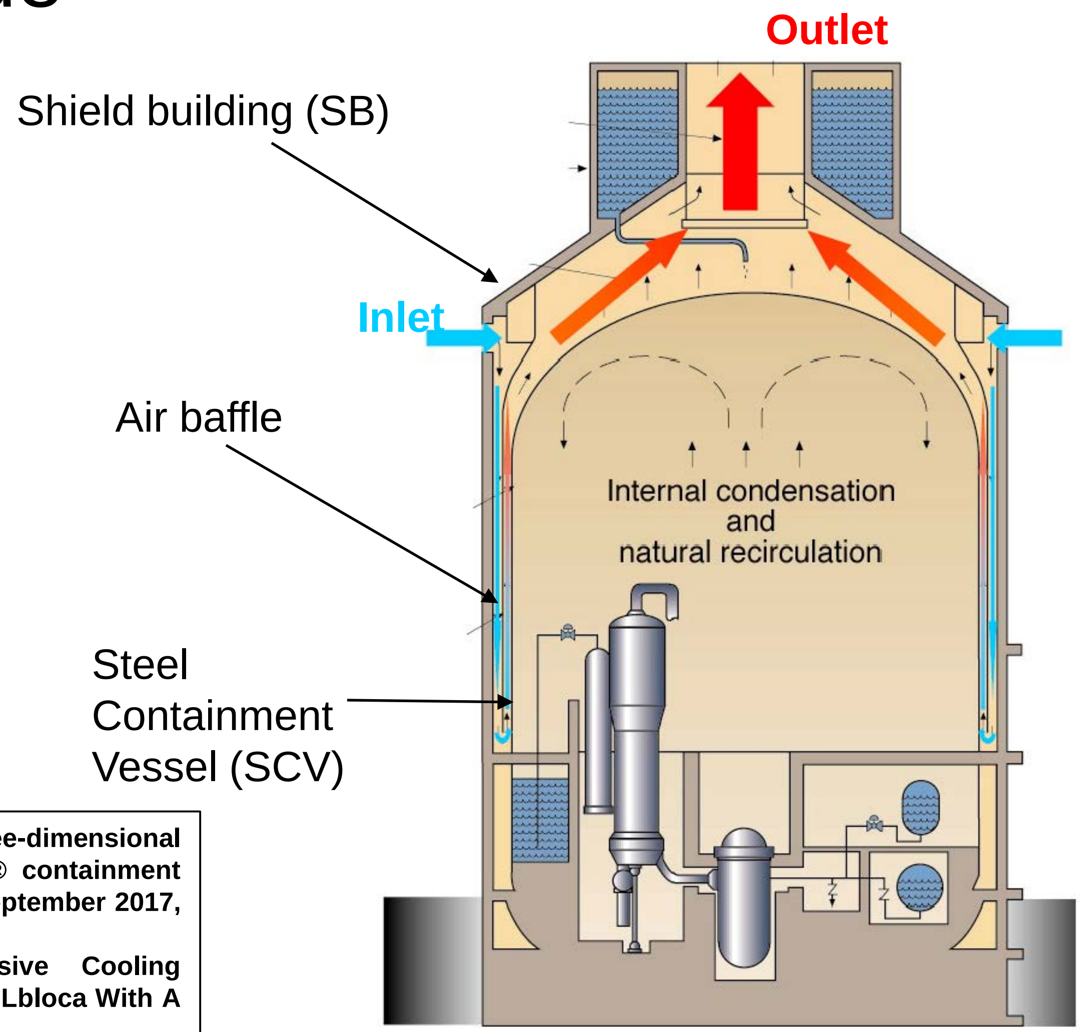
The methodology proposed by UPM and Iberdrola has demonstrated to be efficient for PAR sizing and location.

It allows the implementation of the recombiners based on the preferred Hydrogen pathways and accumulation points

Ref: C. Serrano, et al.. A proposed methodology for the Passive Autocatalytic Recombiner sizing and location for a BWR Mark-III reactor containment building. Annals of Nuclear Energy 94 (2016) 589–602

4. Study of the AP1000 Containemnt with the GOTHIC code

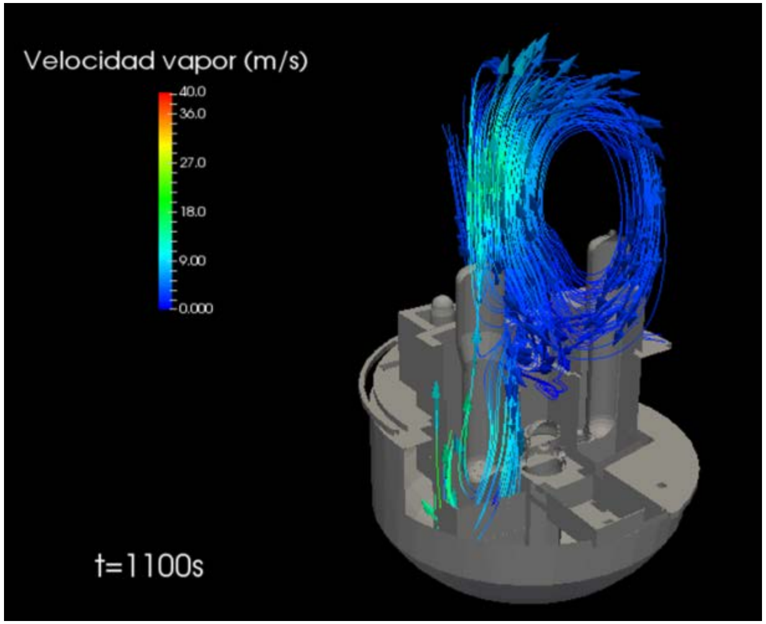
- The phenomena inside an AP1000/CAP1400 containment is both complex and important
- The containment plays an "active role" in the managing of an accident

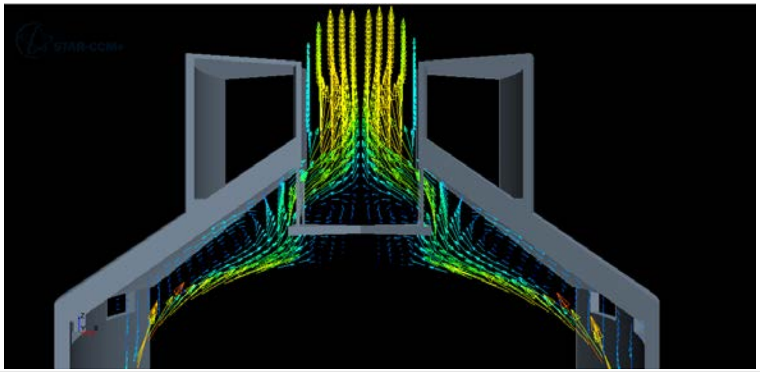


Ref: Kevin Fernández-Cosials et al. Three-dimensional simulation of a LBLOCA in an AP1000® containment building; Energy Procedia Volume 127, September 2017, Pages 234-24
Estévez-Albuja et al. AP1000® Passive Cooling Containment Analysis Of A Double-ended Lbloca With A 3d Gothic Model. ICONE26-81886

4. Study of the AP1000 Containemnt with the GOTHIC code

- Creation of a full containment model for AP1000 with **GOTHIC**
- Creation of a IRWST 3D model with **GOTHIC**
- Creation of a Shield Building model with **STAR-CCM+** and **GOTHIC**
- Simulation of design basis accidents (LBLOCA, SBLOCA) and severe accident (future works)





GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

UPM applications on Large enclosures

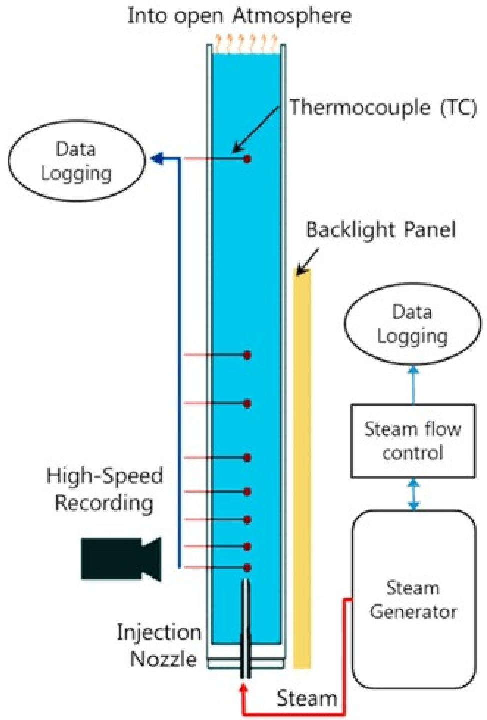
1. Simulation of steam jet into a suppresion pool experiment (TU Munich)
2. Simulation of Hydrogen distribution experiment (PANDA facility, PSI)
3. Simulation of Filtered Containment Venting System of a BWR.

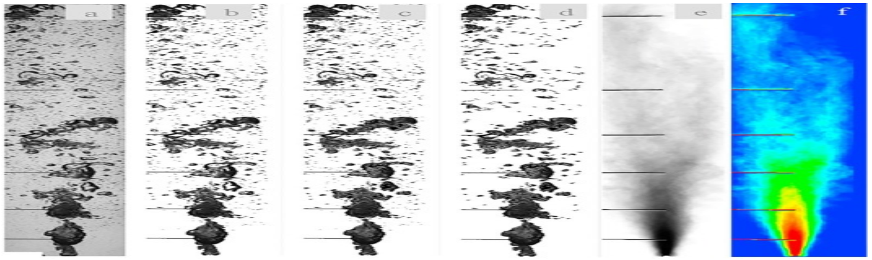
1. Simulation of steam jet into a suppresion pool

- An experiment in TU of Munich (Germany) was performed and simulated with GOTHIC.

- The experiment consisted of a **steam injection** into a channel **filled with water** to simulate the steam injection inside a suppression pool.

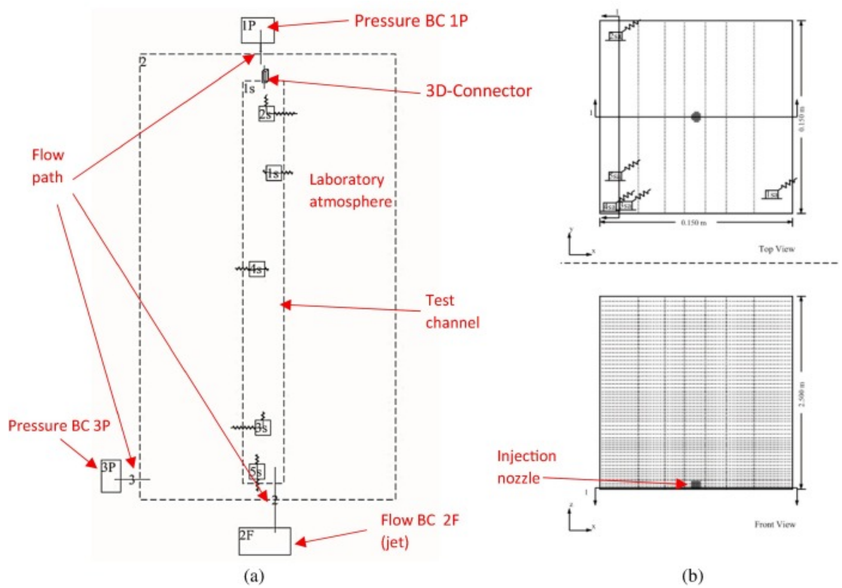
- Thermocouples and high speed camera data was recorded.

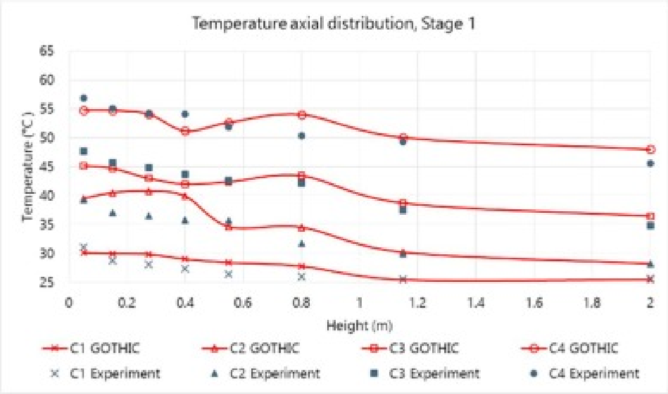


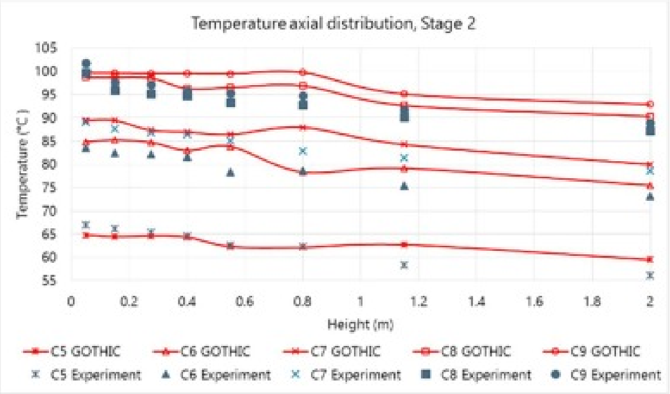


1. Simulation of steam jet into a suppresion pool

- Very **good agreement with** the experiment in terms of temperature at early stages
- **Some discrepancies** are found: Flashing occurs about 500 s earlier in the simulation than in experiment



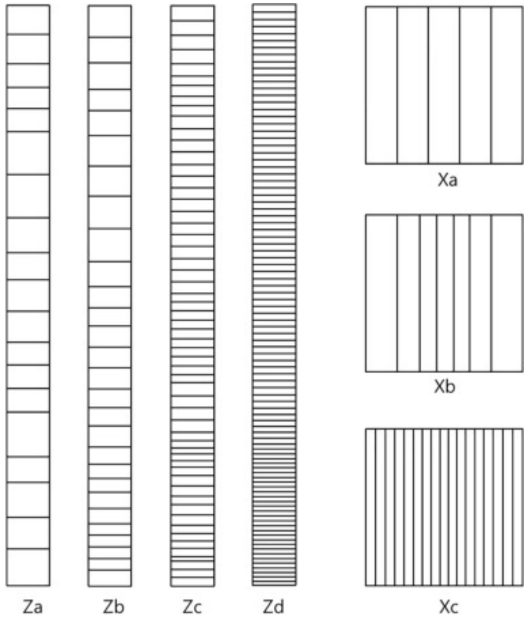


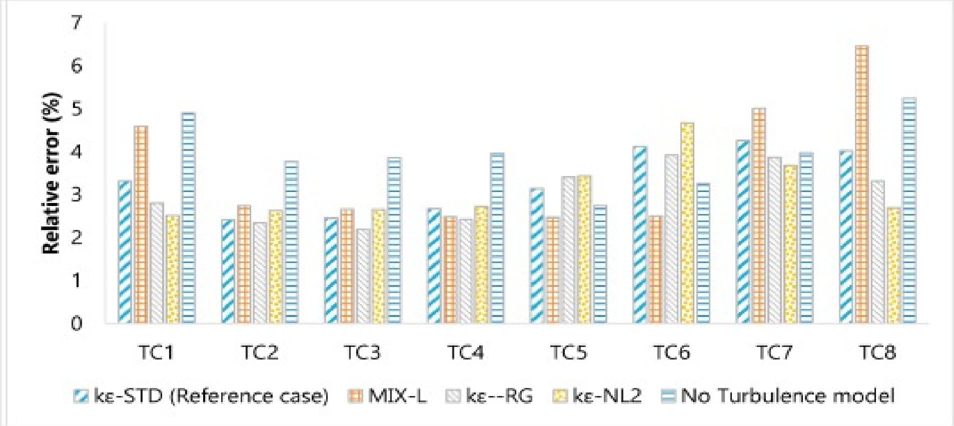


1. Simulation of steam jet into a suppresion pool

Given the GOTHIC low computational effort, a **wide sensitivity analysis** can be performed:

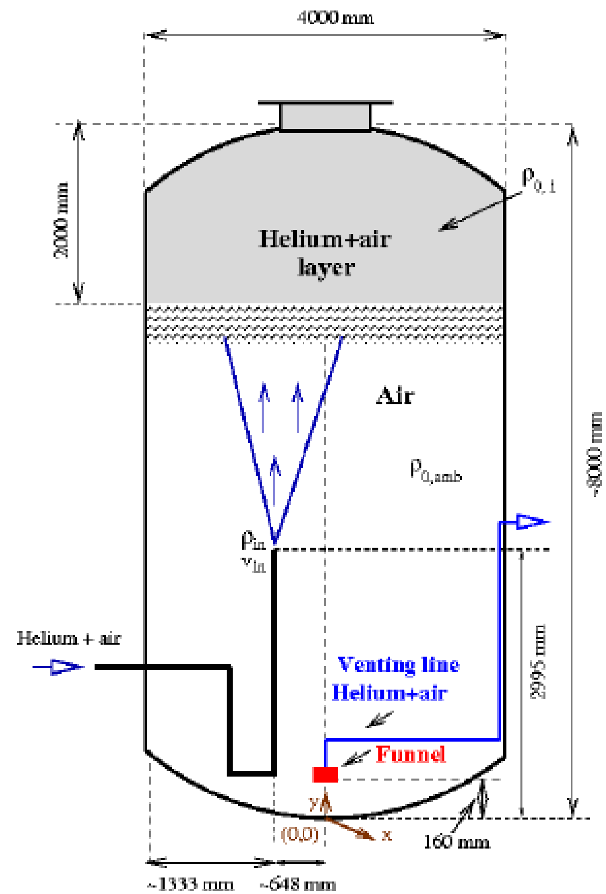
- The mesh was studied in different configurations.
- Different turbulence models were assessed
- Different discretization schemes
- Different Heat transfer options.





2. Simulation of Hydrogen distribution experiment

- An experiment conducted in the Paul Scherrer Institute (PANDA facility was simulated with GOTHIC as part of the International Benchmark Exercise III
- The experiment consisted of a **light gas injection** into a large enclosure filled with a stratification layer of Helium.
- Temperature, Concentration and velocities data was recorded.



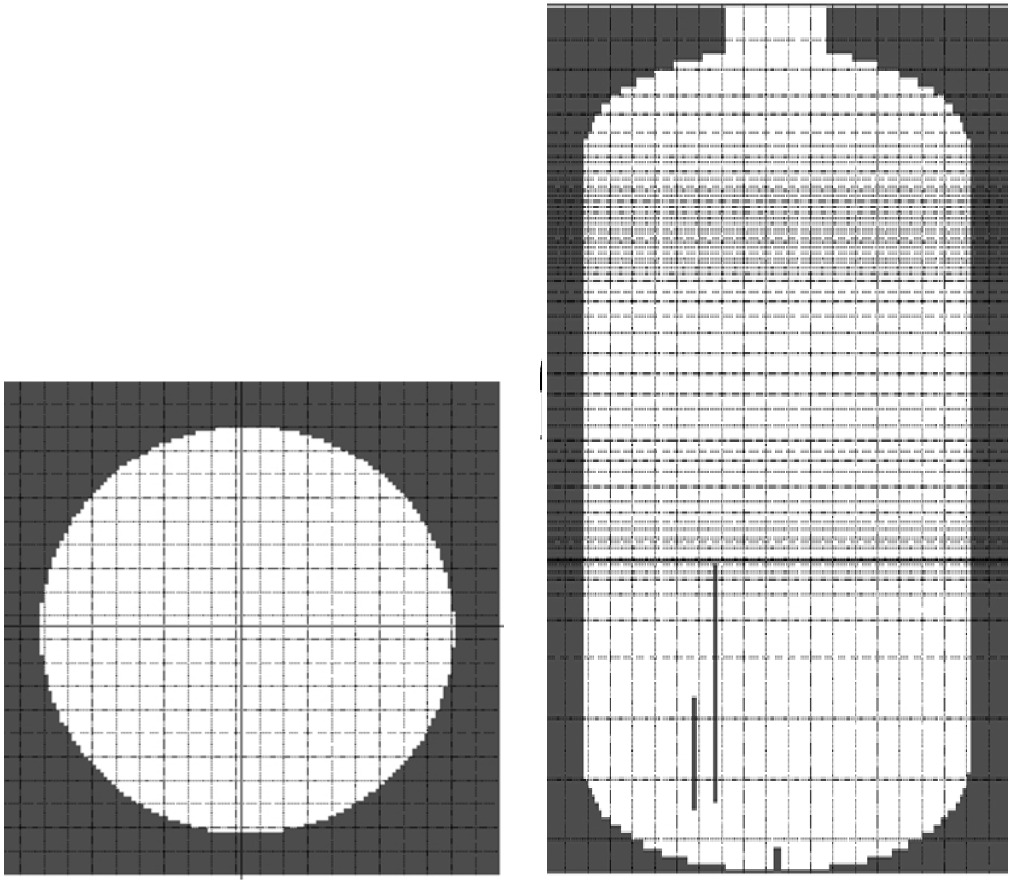
Ref: Kevin Fernández-Cosials et al. Analysis of a gas stratification break-up by a vertical jet using the GOTHIC code. Nucl Eng Des 2016; 297:123–35. doi:10.1016/j.nucengdes.2015.11.035.

2. Simulation of Hydrogen distribution experiment

- An **integral model** of the vessel in 3 D with a relative coarse mesh (relative to CFD codes) was created.

- A refinement in the most important zones is used.

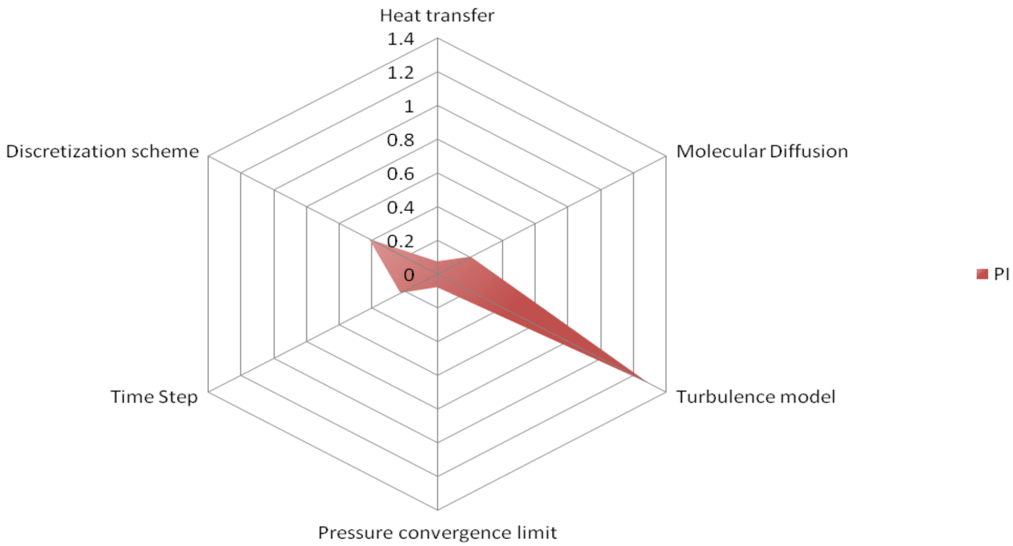
- The mesh has to be carefully designed to allocate the sensors in the cells center.



Ref: Kevin Fernández-Cosials et al. Analysis of a gas stratification break-up by a vertical jet using the GOTHIC code. Nucl Eng Des 2016; 297:123–35. doi:10.1016/j.nucengdes.2015.11.035.

2. Simulation of Hydrogen distribution experiment

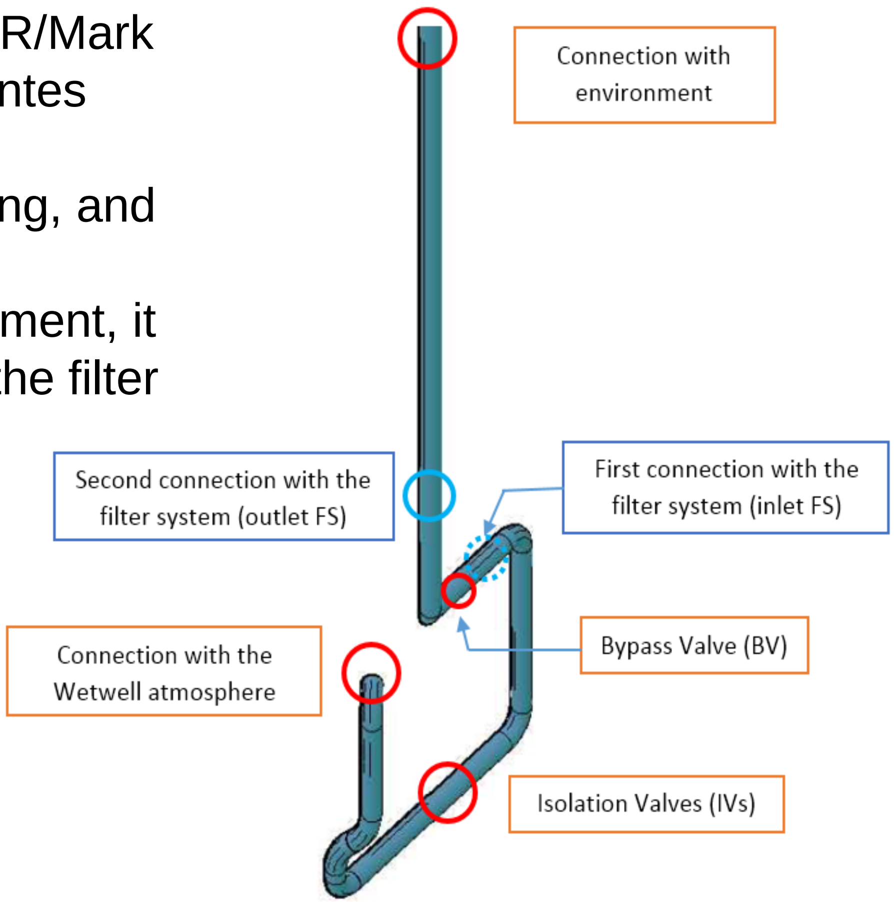
- As usual, the low computational effort permit a wide sensitivity analysis for this phenomena
- The sensitivity analysis reached to a simulation **more accurate** than all the participants of the IBE-III of the pre-test.
- The sensitivities were analyzed according to their impact on the simulations results.

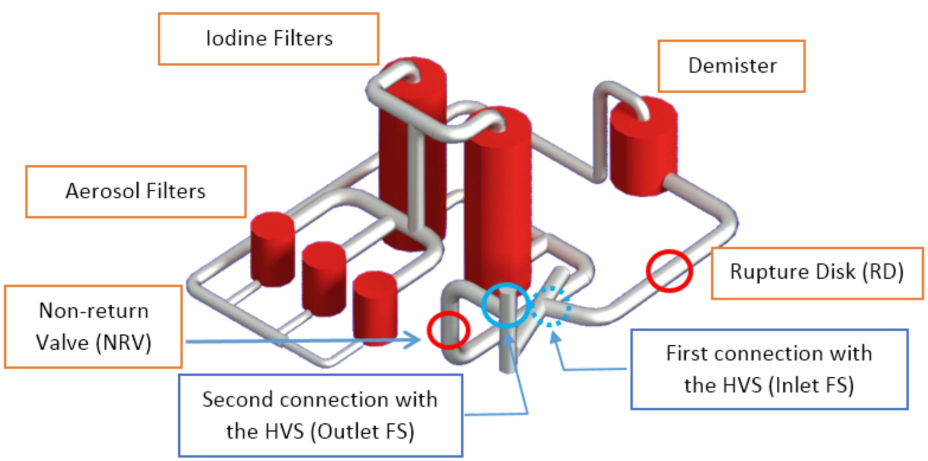


Ref: Kevin Fernández-Cosials et al. Analysis of a gas stratification break-up by a vertical jet using the GOTHIC code. Nucl Eng Des 2016; 297:123–35. doi:10.1016/j.nucengdes.2015.11.035.

3. Simulation of Filtered Containment Venting System of a BWR

- The Filtered Venting system of a BWR/Mark III containment is being built in Cofrentes NPP
- It involves a bypass of the hard venting, and includes aerosol and iodine filters.
- If **hydrogen** is present in the containment, it can reach deflagration conditions in the filter

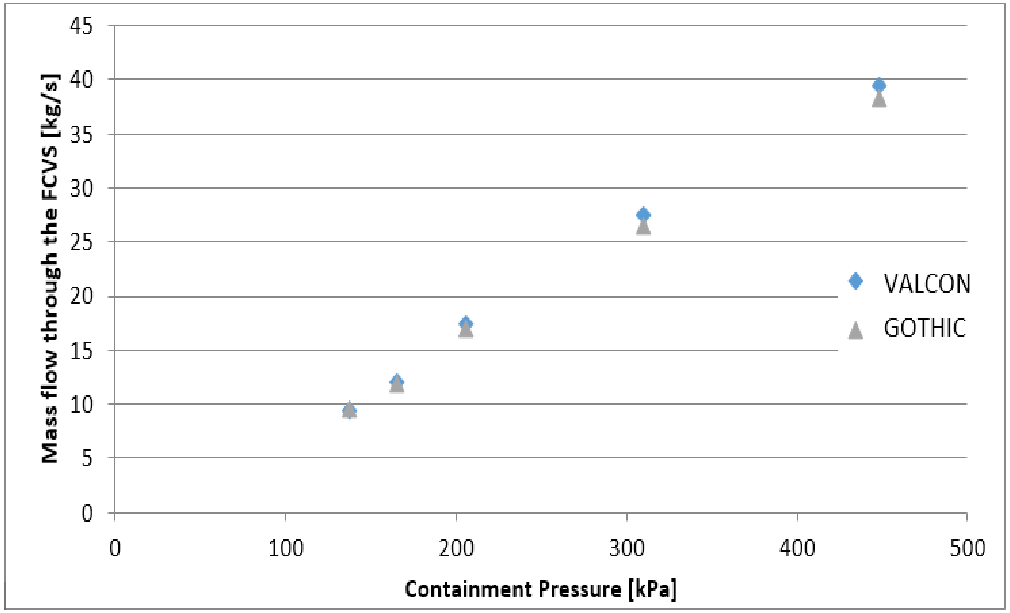




Fernández-Cosials, K et al. , 2018. Analysis of Inertization Strategies for the Filtered Containment Venting System in Cofrentes Nuclear Power Plant. Journal of Nuclear Engineering and Radiation Science 4, 031016.

Applications of the GOTHIC code

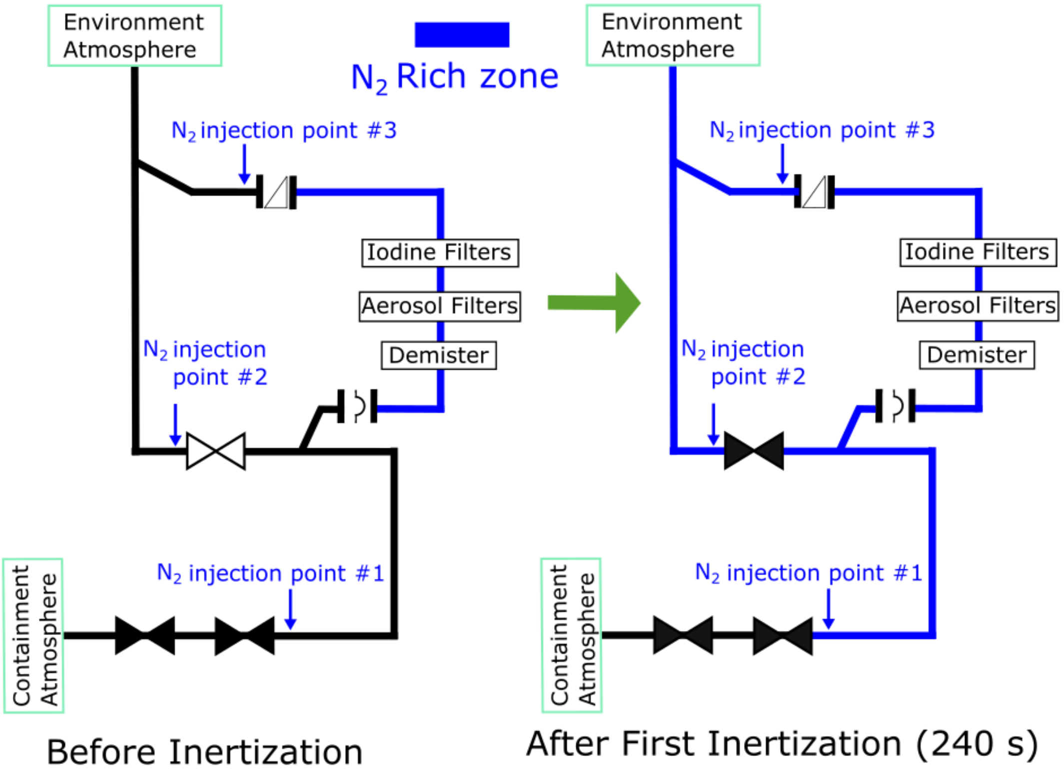
- An Integral GOTHIC Model of the pipe and filtered system is used.
- The comparison of mass flow between GOTHIC and a pipe-specific code provides **almost identical results** of a venting during a SBO.



Fernández-Cosials, K et al. , 2018. Analysis of Inertization Strategies for the Filtered Containment Venting System in Cofrentes Nuclear Power Plant. Journal of Nuclear Engineering and Radiation Science 4, 031016.

Applications of the GOTHIC code

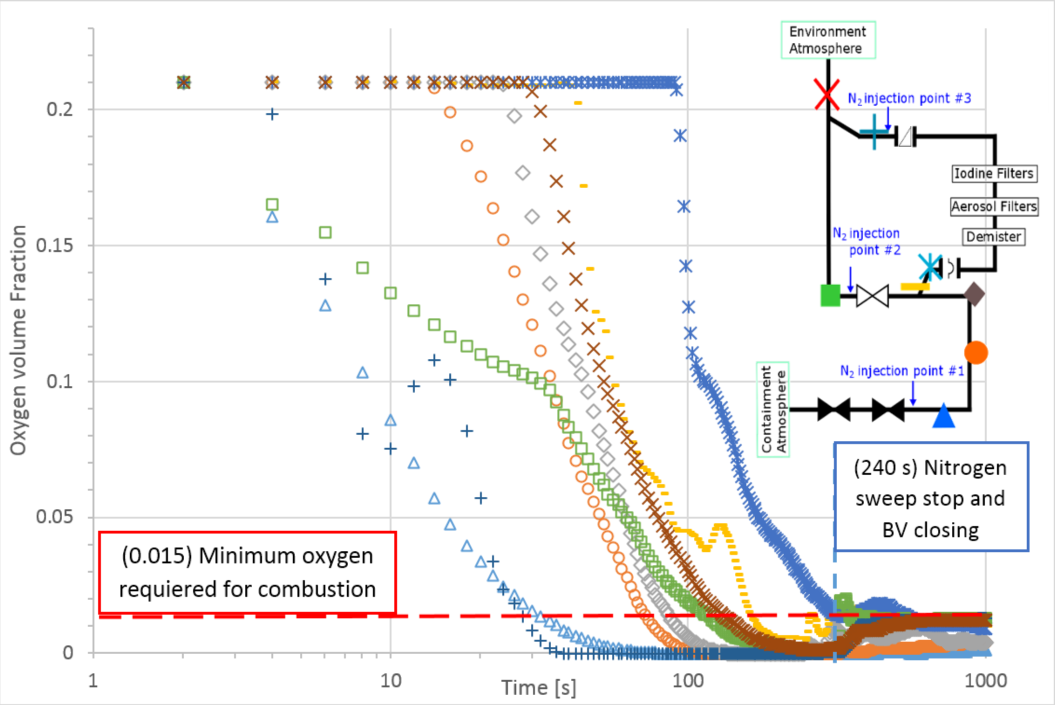
- After finding hydrogen risk during the simulation with GOTHIC, it was later used to locate and size the **Nitrogen sweep** injections
- Three injection points were identified to sweep dead-ends with stagnant air.
- The sweep displaces all the oxygen, so it cannot react with the hydrogen



Fernández-Cosials, K et al. , 2018. Analysis of Inertization Strategies for the Filtered Containment Venting System in Cofrentes Nuclear Power Plant. Journal of Nuclear Engineering and Radiation Science 4, 031016.

Applications of the GOTHIC code

- After the Nitrogen Sweep the hydrogen risk was eliminated during the first venting.
- If the Filter System is not inerted, the Nitrogen Sweeps still eliminated the
- The opening time and duration of each injection is established with GOTHIC.



Summary

- GOTHIC Containment 3D modelling capability has been deeply studied
- More accuracy and detail than the LPM can be obtained, leading to local analysis in large enclosures
- The lower computational cost than a commercial CFD allows to deeply study a sequence through sensitivity analyses.
- The containment codes 3D capabilities may influence in the way containment licensing is currently done.

Future Research Lines

- Different containments development (VVER/AES, EPR) or large enclosures (PANDA, TOSQAN, Thai…)
- Application of containment 3D analysis to create the enveloping profile for EQ (using LOCAs and MSLBs)
- Include Equipment & Instrumentation Failure location during a DBA or SA.
- Application of the Tau parameter to compare hydrogen risk of a wide range of accident simulations
- BEPU analysis, taking advantage of the small computational effort relative to commercial CFDs

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3. Analysis of the equipment and instrumentation qualification criteria using 3D containment models. G. Jimenez, K. Fernandez-Cosials, R. Bocanegra, C. Queral. Nuclear Engineering and Design 323 (2017) 28–38.
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Recent research of the UPM Nuclear Safety Group with the GOTHIC code

Paul Scherrer Institute (Switzerland)
04/04/2019

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