Economic Commission for Europe

Inland Transport Committee

Working Party on the Transport of Dangerous Goods

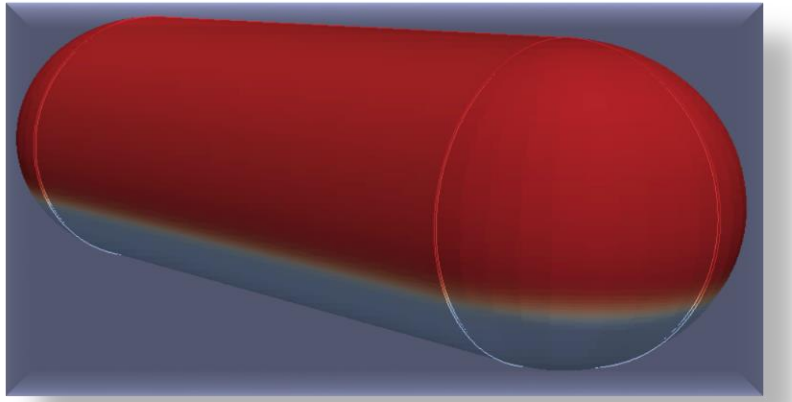
Joint Meeting of the RID Committee of Experts and the Working Party on the Transport of Dangerous Goods
Bern, 13–17 March 2017
Item 2 of the provisional agenda
Tanks

20 February 2017

Model for the thermal response of Liquefied Petroleum Gas Tanks subjected to accidental heat input

Transmitted by the Government of France

Model for the thermal response of Liquefied Petroleum Gas Tanks subjected to accidental heat input



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RID ADR JOINT MEETING 03-2017

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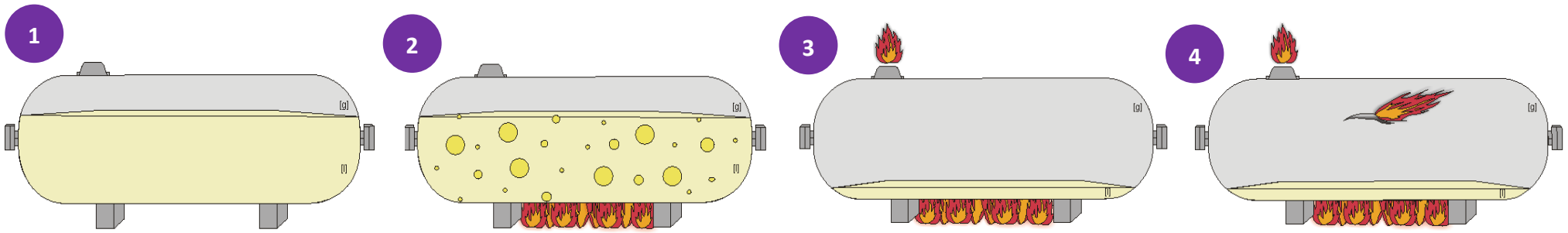
Summary

- Context
- INERIS Model presentation
  - Model description
  - Model validation : results comparison with experimental data
- Model results for real scale tanks
  - Calculations on tanks equipped with coatings and/or safety valves
- Conclusion
  - Model limitations
  - Experimental tests required

BLEVE scenario

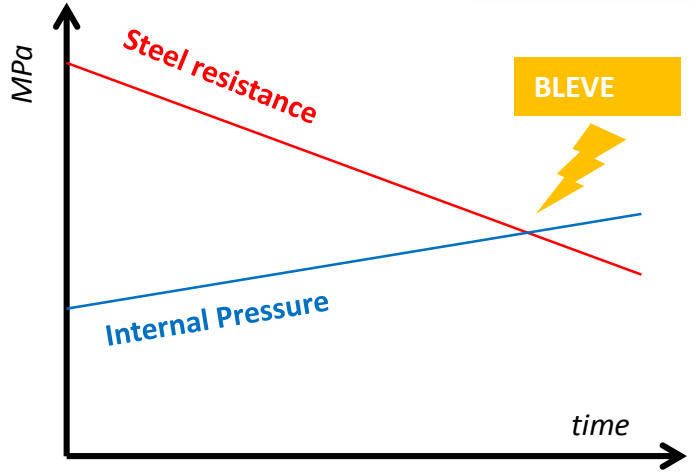


The tank is filled

Tank is located in fire
Boiled liquid

Pressure increases
Liquid level drops
Safety valve opens

Pressure continues to rise
Strength reduction of steel
Tank wall cracks



Behaviour diagramm of the tank

Context

- Working group on the reduction of the risk of a BLEVE during transport of dangerous goods
  - Aim: To study the equipment of tanks with safety valves and/or fire protection coatings
  - 2013-2014: **Tests carried out by BAM** to assess response of low capacity LPG tanks under thermal loads (capacity : 2,75 m^3)
  - TNO: qualitative validation with an analytical approach => extension to larger tanks
- Main conclusion: Thermal coatings and safety valves or their combination may delay or avoid BLEVE
- 2015: French competent authority requests INERIS to use its predictive tool to study the behaviour of different configuration tanks:
  - Tanks with safety valve
  - Tanks with fire protection coating
  - Tanks with fire protection coating and safety valve
- Objective: To assess the response of LPG tanks under thermal loads for various tank geometry and different kinds of thermal protection (tank capacity, safety valve size,…)

Description

Methodological approach used for INERIS model

Input

- Steel wall characteritics (diameter, thickness,…)
- Thermal protection (safety valve, coating)
- Lading characteristics (Level filling, Products)
- External thermal load characteristics

MECHANICAL MODEL ⟷ **THERMAL MODEL**

Failure Criterion : Loss of containment

Model Results

- ✓ Temperature distribution in the tank shell
- ✓ Temperature distribution in the lading
- ✓ Pression evolution
- ✓ Level filling evolution
- ✓ Stress cartography in the tank shell

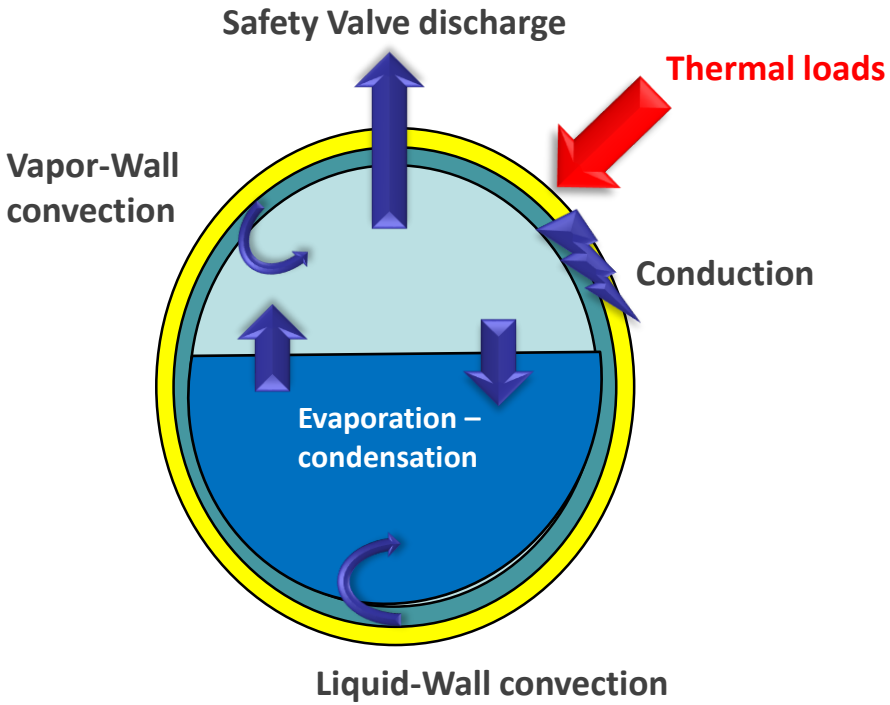
No collapse → ✓ Effective protection

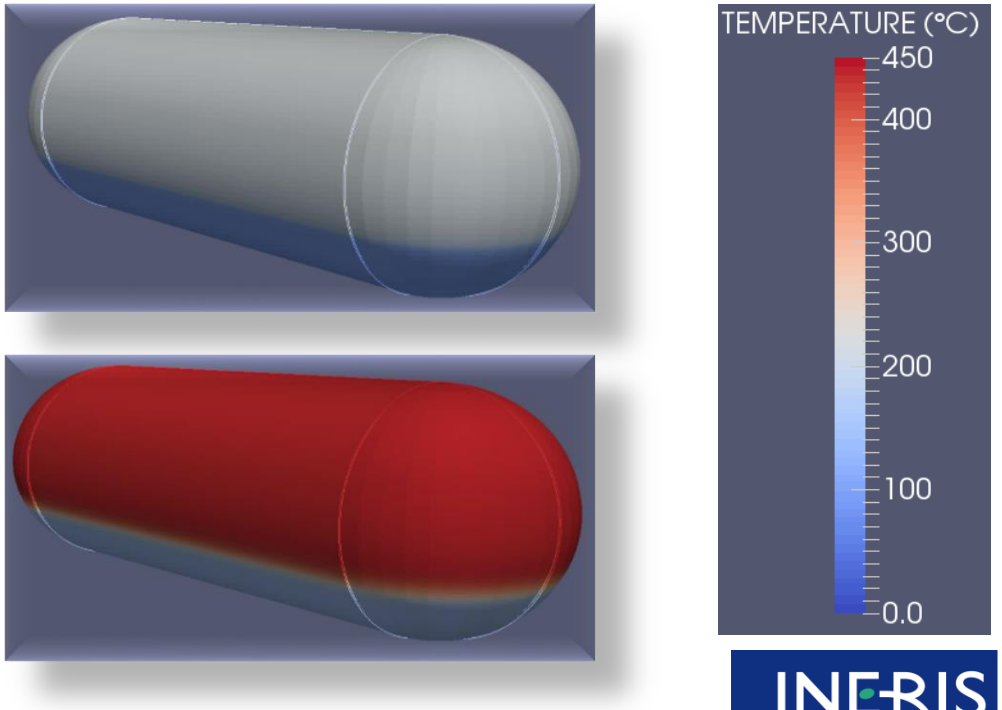
Collapse → ✓ Effectiveness of the measure depending on time to failure (to be defined by authorities)

✓ Non effective protection

Description

- Models characteristics
  - Finite elements model for the tank shell (insulation + steel wall)
  - Analytical approach with a 2 phase model for the content. This model provides relevant results for tanks with a maximum capacity as used in transport (up to 100 - 150 m^3). This approach is widely used in industry (ex : Vessfire software developed by Petrell As)
  - **Objective**: To predict the temperature (for both phases) and pressure evolution of tanks (with or without coatings) when submitted to heat input.





Thermal transfers in LPG tanks under thermal loads

Validation

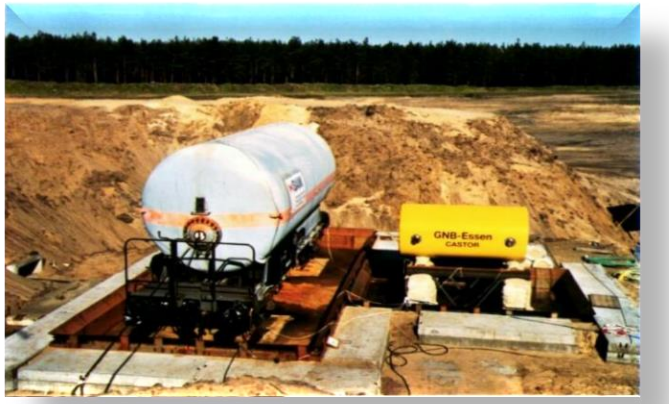
- INERIS model has been compared with several experimental data. Test characteristics are summarized in the table below.

Test Number	1	2	3
Description	BAM (Bundesanstalt für Materialfosrschung und –prüfung) Tests- Large scale test carried out in 1998	Vessfire Test - Large scale test carried out by Petrell As to validate their model	BAM - Medium scale test in the framework of the Working Group on the reduction of BLEVE Risk (2013-14)
Volume (m^3)	45	10.25	2.75
Filling rate (%)	22	22	50
Safety valve or thermal coating	-	Safety Valve	Thermal coating

- These 3 tests consist in applying a full fire engulfment on the tank shell containing LPG
  - Tanks equipped with monitoring system (temperature and pressure sensors)
  - Representative tests including various geometries and various protection systems (insulation & valves)

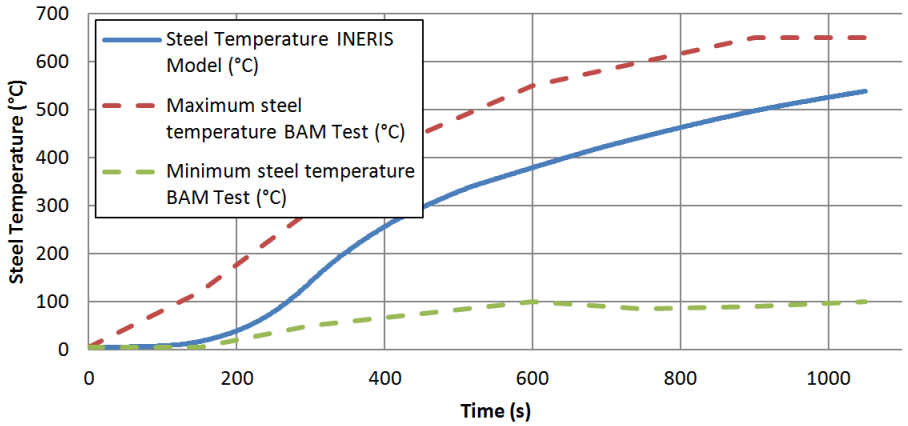
Validation : Test 1 - BAM

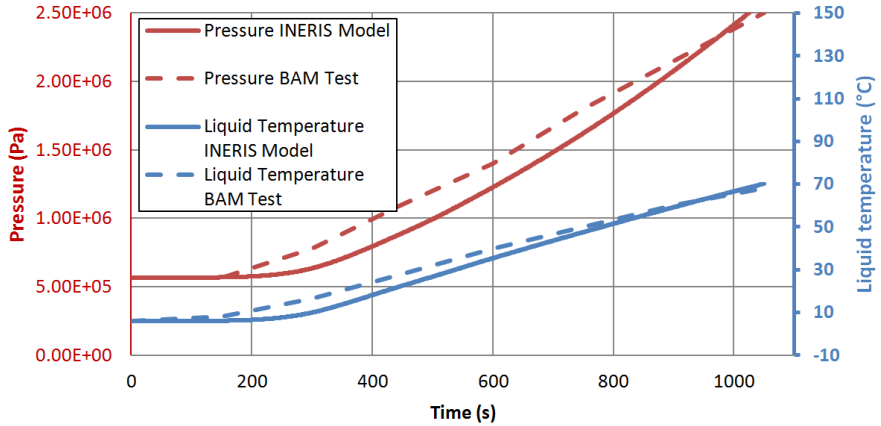
- These test results are now widely used to develop BLEVE effect models (Distance effects for blast/thermal effects)
- Several scientific publications emerged following to this test
  - Impact of an exploding LPG rail tank car onto a castor spent fuel cask (Droste et al. BAM)
  - Analysis of a propane Sphere BLEVE (A.M. Birk et al. – Queen's University)



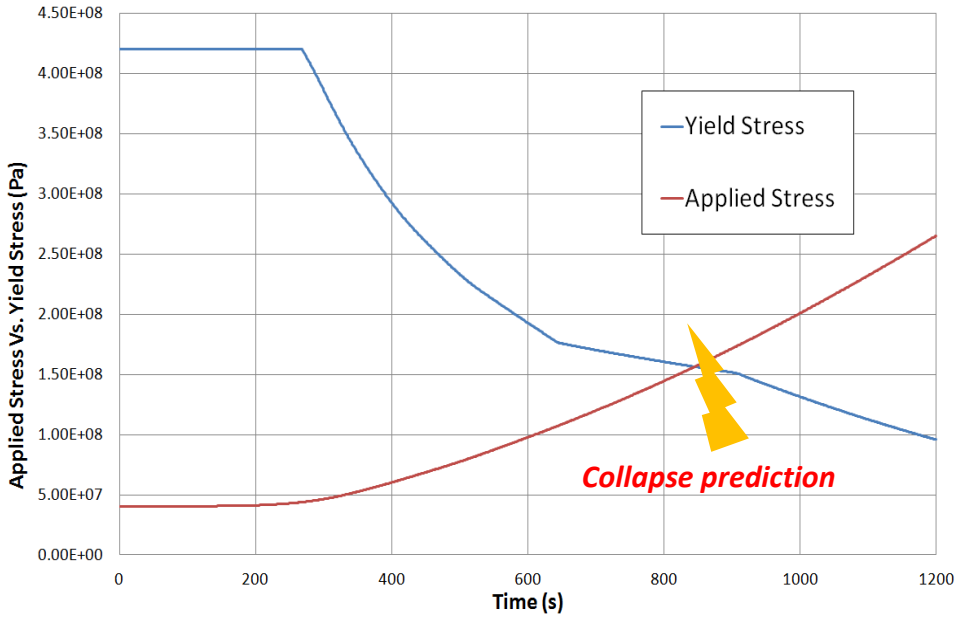
Validation : Test 1 - BAM

- Test results: Pressure and thermal evolution





Pressure & Temperature evolution are similar between BAM Test and INERIS Model



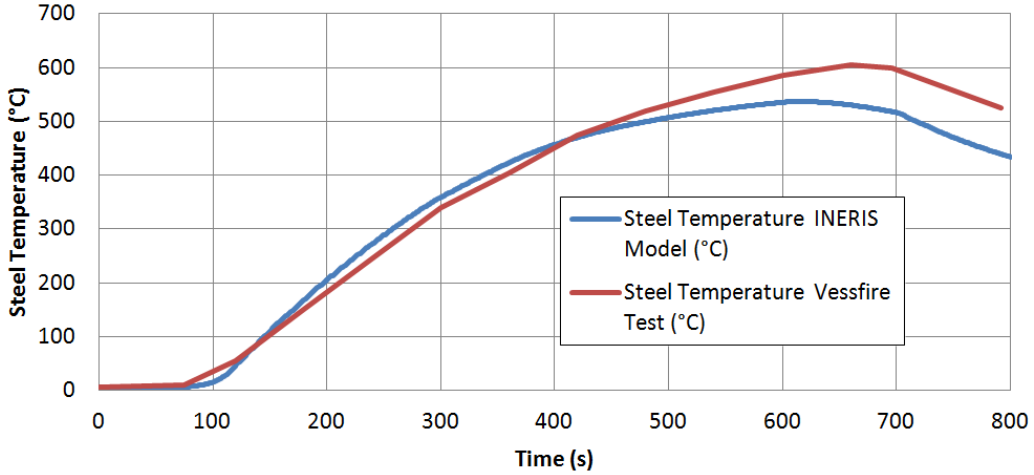
Time before collapse assessed by INERIS is shorter than the value observed during the test

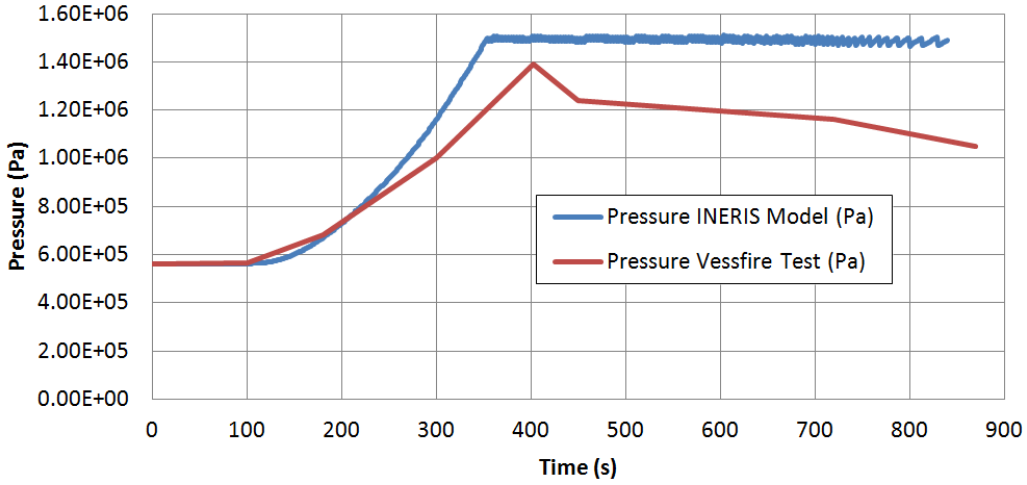
Time before collapse occurs	
INERIS Model	**BAM Test**
850 seconds	1050 seconds

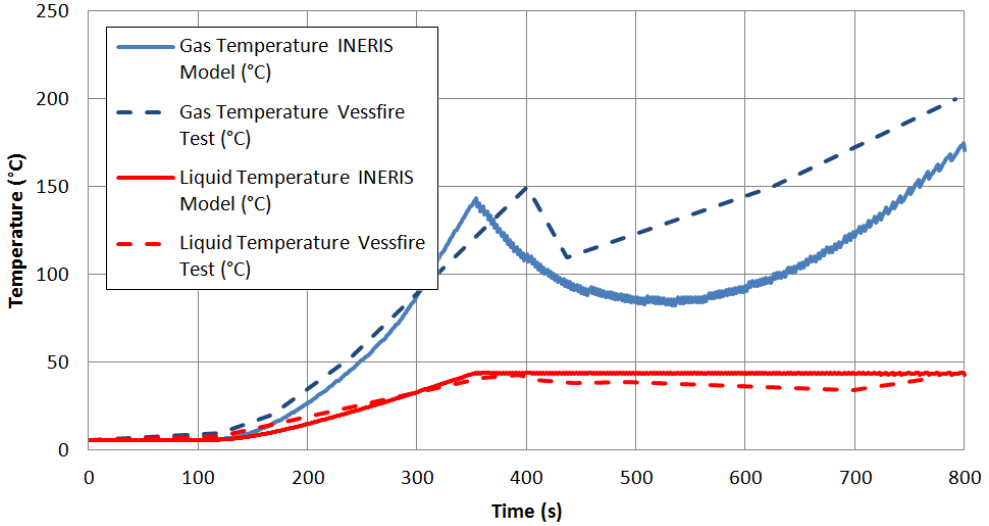
A more conservative approach is used in the INERIS model (elastic behaviour of material)

Validation : Test 2 - Vessfire Test

- Tests well-documented and widely used in the literature to validate models







Model results are in accordance with test measures for the steel temperature, the pressure and both phase temperatures

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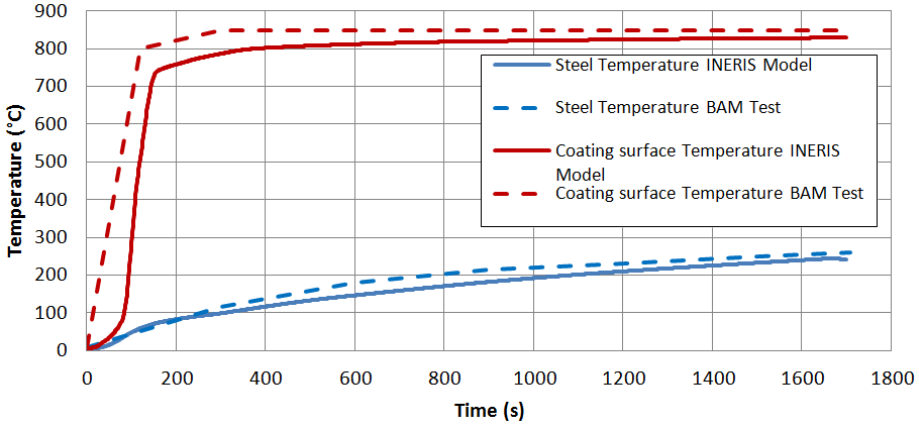
Validation : Test 3 - BAM

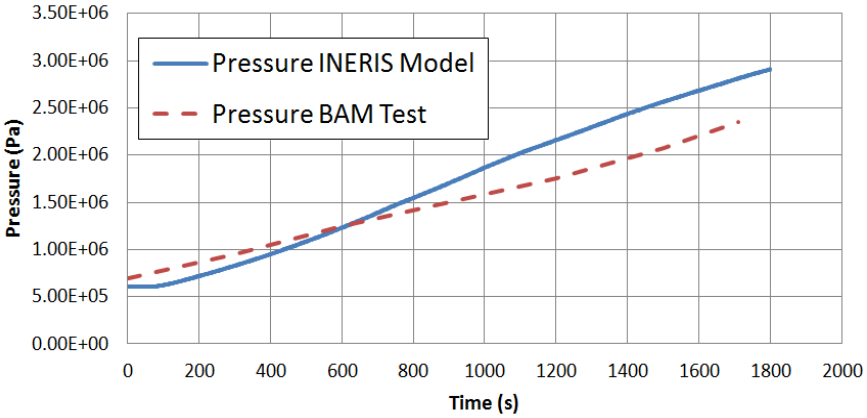
- BAM test carried out in the frameworks of the Working Group dedicated to “BLEVE reduction” in 2013
  - Test carried out to evaluate the efficiency of thermal coating
  - To avoid the BLEVE, test was interrupted when the following criteria were fulfilled: P=25 bar & T_{steel}=350°C

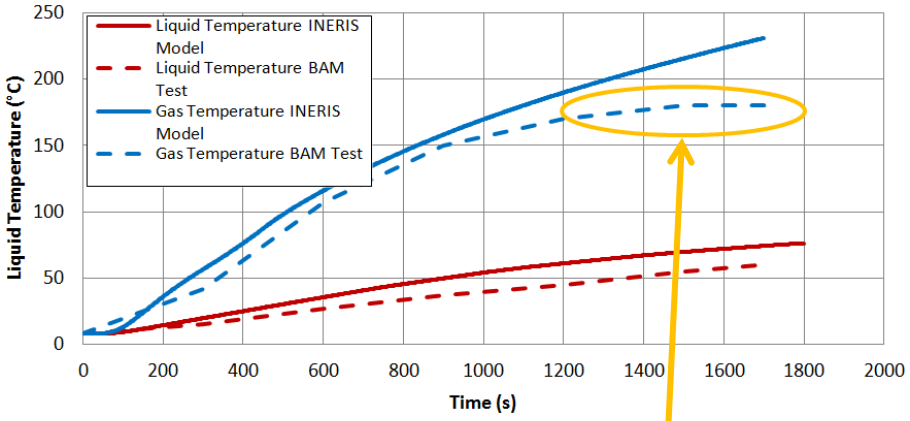
View of the tank after the test

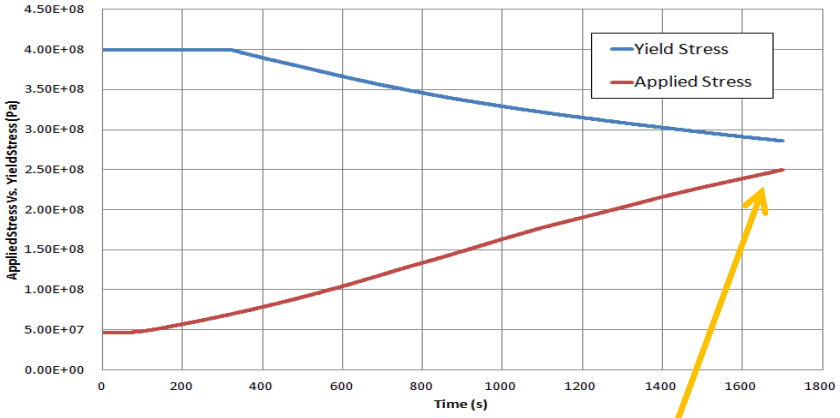
Validation : Test 3 - BAM

- Test results









The gas thermocouple was temporarily wetted due to the boiling lading. This explains the results difference between the test and the model from 1200 s to 1800 s

Test halted after 28 minutes to avoid BLEVE => The stress curve obtained with INERIS model shows the imminent BLEVE

Model results are in accordance with test measures for this test

Model Results for real scale tanks

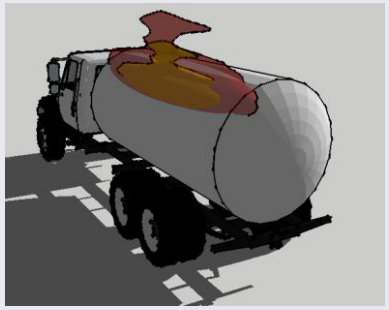
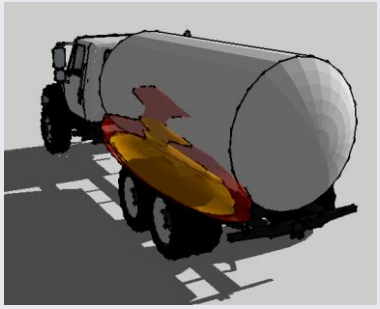
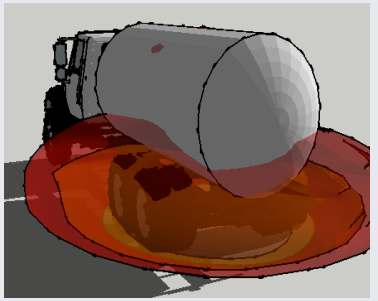
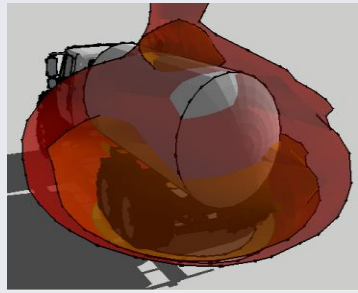
Introduction

- Comparisons carried out between numerical results & experimental data demonstrate the reliability of the model to predict the response of tanks subjected to fire
- Several questions have been raised by the Working Group dedicated to “BLEVE reduction”:
  - What is the efficiency of thermal coatings and safety valves in the event of a fire?
  - Are these protection measures efficient whatever the fire and the tank configuration?
- Tests carried out by BAM have partially answered these questions for small tanks :
  - Thermal coatings are efficient to delay the BLEVE
  - Safety valve may stabilize the internal pressure of the lading. However the safety valve used during the test did not allow to protect the tank from BLEVE.
- The numerical model allows to play with different scenarios and simulate the behaviour of different tank types in different fires. For the time being, the following have been done :
  - 2 existing tank geometries have been studied : 31 & 60 m^3
  - Tanks are exposed to small / large fires on liquid or gas phase (heat flux of 100-150 kW/m^2)
  - 2 protection concepts: safety valves and thermal coatings

Model Results for real scale tanks

Tanks equipped with safety valves

- The following table summarizes configurations studied by INERIS
- Each calculation is led for 2 configurations: with and without safety valve

Calculation Number	1	2	3	4	5
Fire scenarios	Small Fire on gas phase	Large Fire on gas phase	Small Fire on liquid phase	Large Fire on liquid phase (Pool fire)	Full Fire engulfment (Pool fire)
					

- The target is an LPG tank whose characteristics are described below :
  - Filling rate: 50%
  - Volume: 31 m^3
  - Common PRV (diameter: 2'' & $P_{opening}$:16.5 bar)

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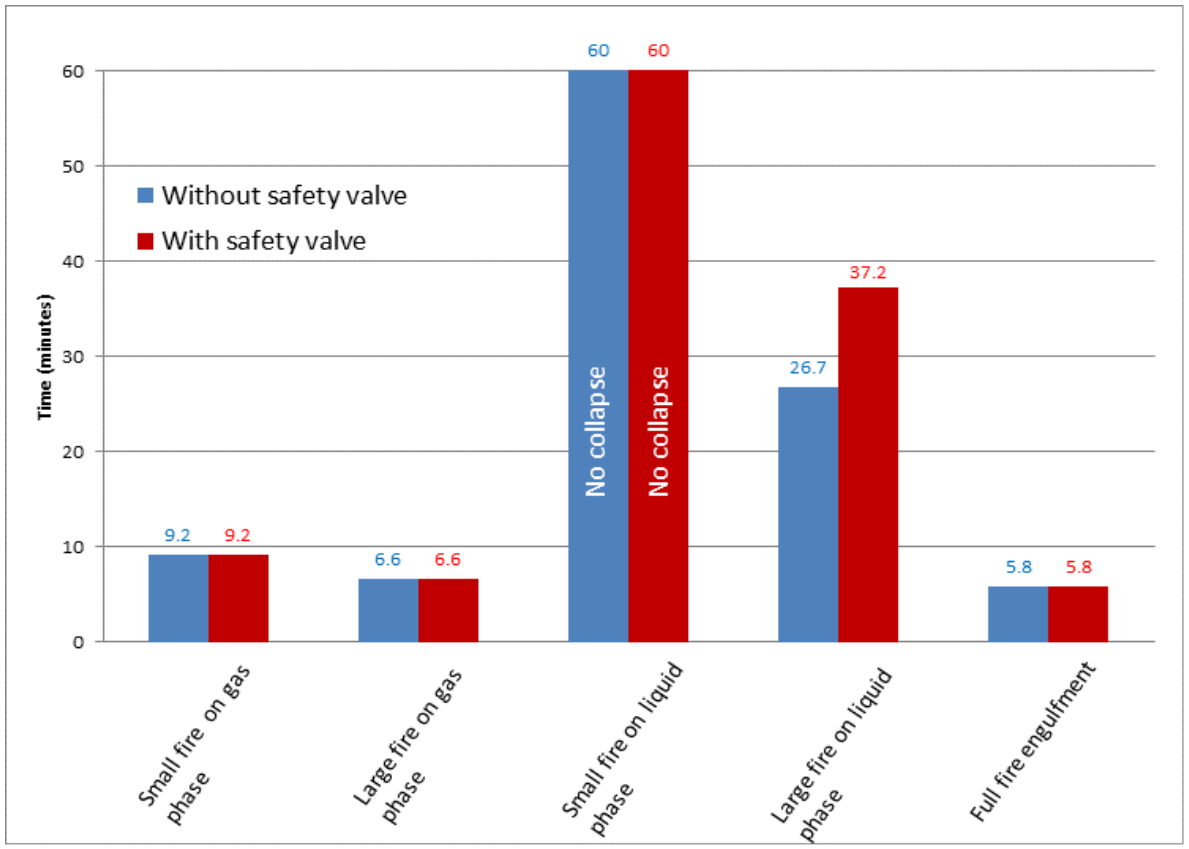
Model Results for real scale tanks

Tanks equipped with safety valves

- The figure below show the time to rupture calculated in different cases of fire with/without safety valve (PRV) (semi-trailer 31m^3 – Valve 2” & $P_{opening}$:16.5 bar)
- A rupture time of 60 min indicates that there is no rupture within the 60 min time limit

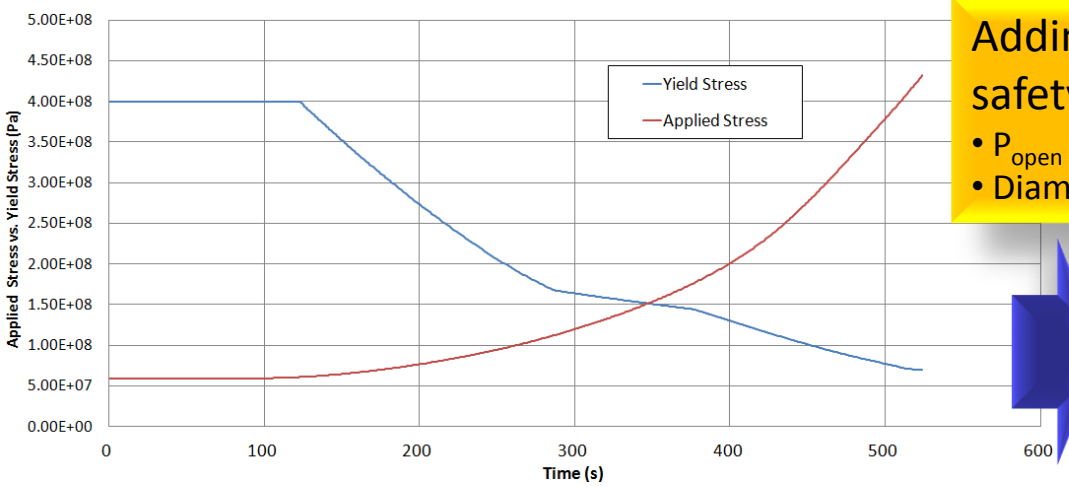


- In most cases, safety valve is not efficient as the opening pressure (16.5 bar) is higher than the collapse pressure (~14 bar at T_{steel}: 500°C)

Model Results for real scale tanks

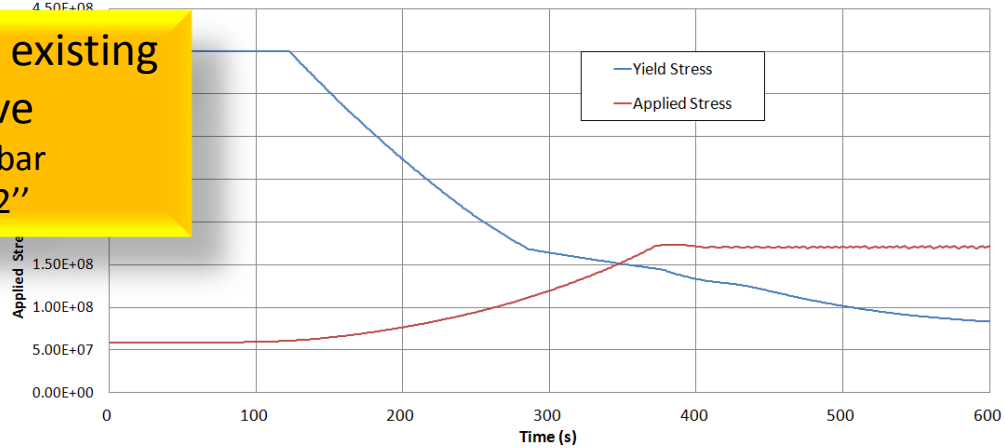
Tanks equipped with safety valves

- Focus on case N°5: Full fire engulfment



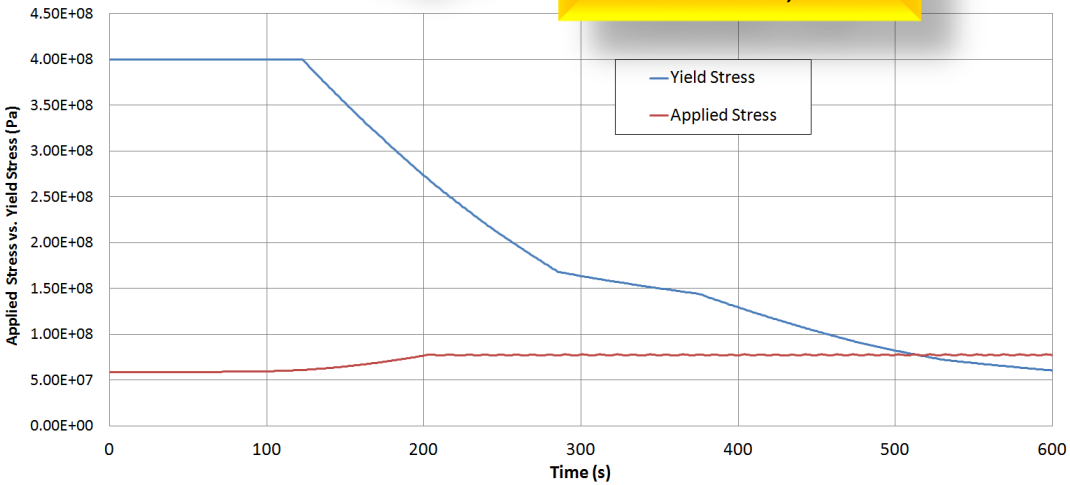
Adding an existing safety Valve

- P_{open} : 16.5 bar
- Diameter : 2''



Adding a fictive safety Valve

- P_{open} : 8 bar
- Diameter : 2,4''



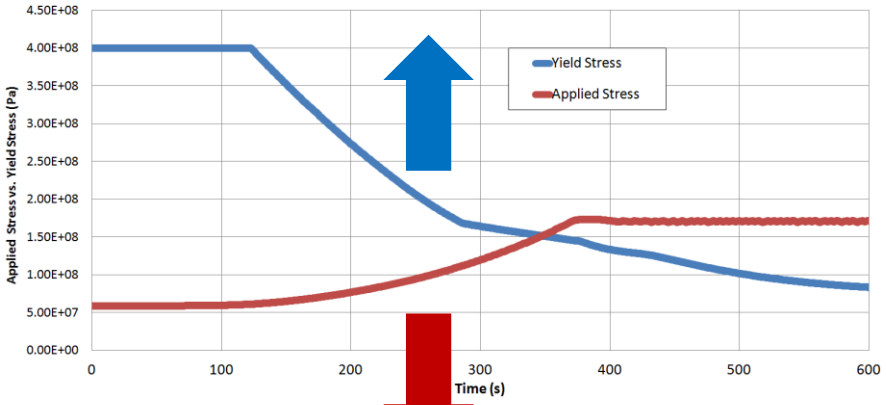
- Commonly used safety valve are not efficient in that case
- No safety valve could be efficient in that case: the allowable pressure after 600 seconds, equals to the operating pressure (6 bar)

Model Results for real scale tanks

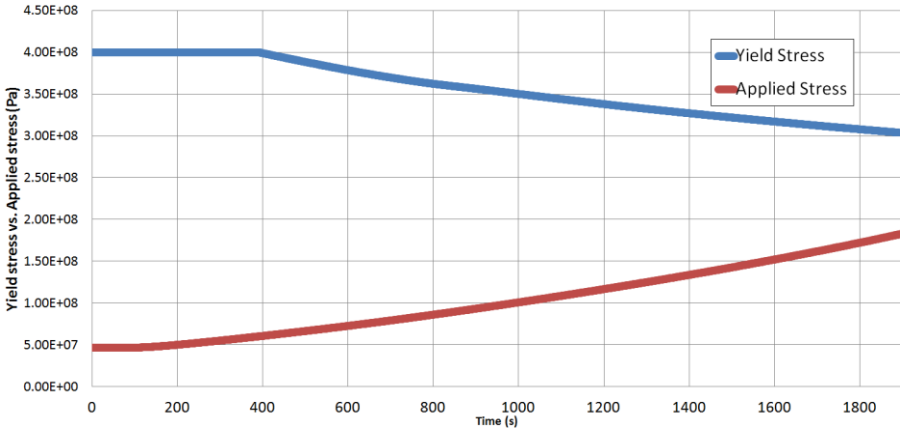
Tanks equipped with safety valves

- Focus on case N°5: Full fire engulfment
- How to improve the tank performance to heat input?
  - Decrease the applied Stress curve
  - Increase the Yield Stress curve

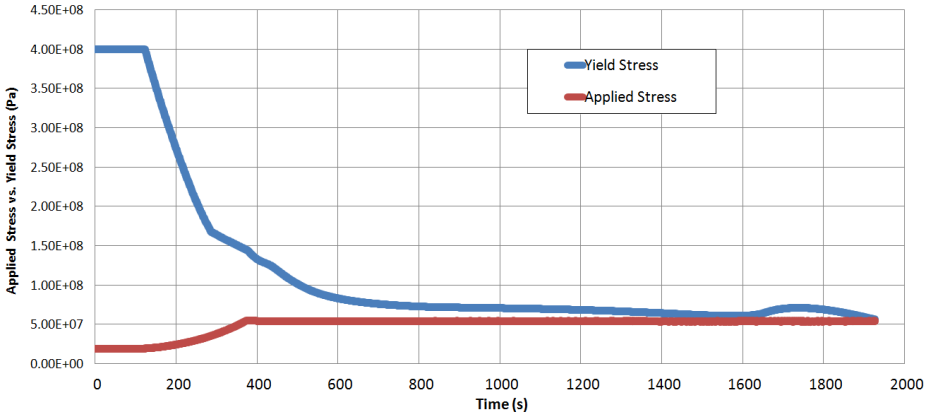
Strategy to increase the blue curve:
- improve steel characteristics (Yield Stress)
- adding a thermal coating



Strategy to decrease the red curve:
- increase the steel thickness
- adding a thermal coating



Results for a tank equipped with a thermal coating



Results for a tank with steel thickness: 3 cm

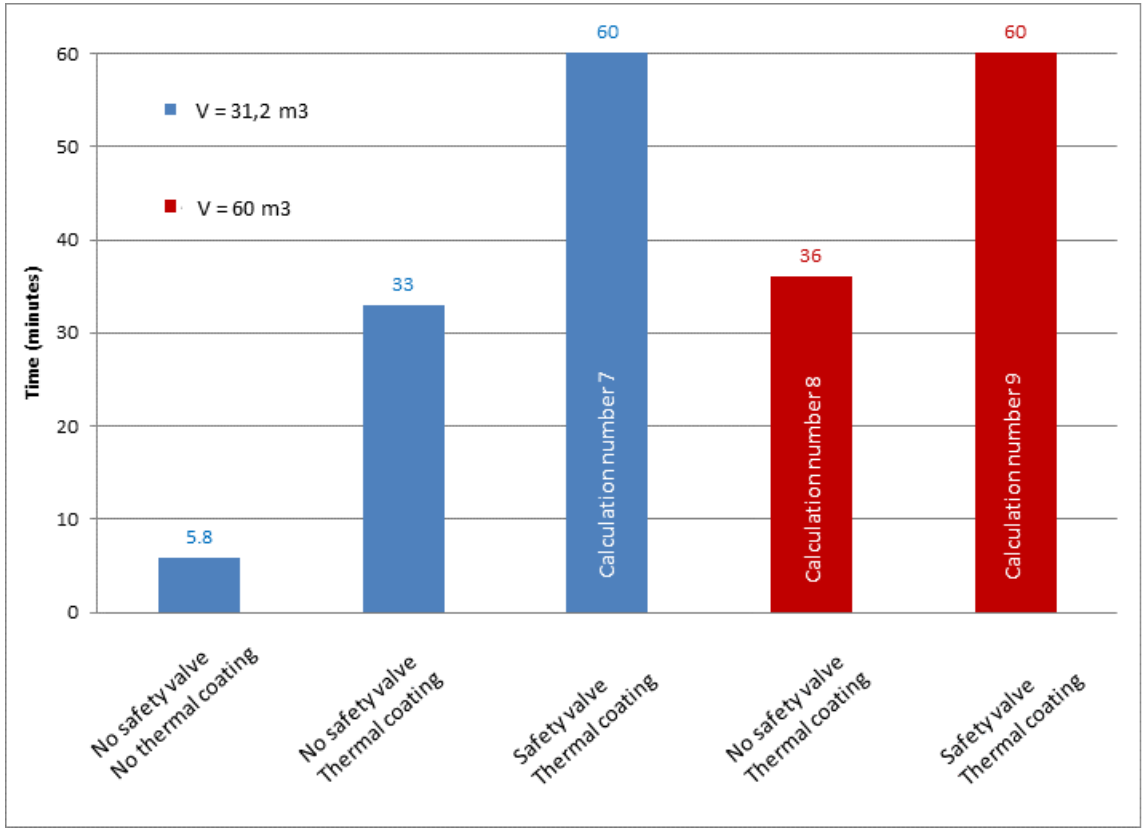
Model Results for real scale tanks

Tanks equipped with thermal coating

- Calculation characteristics are described below
  - Filling rate: 50%
  - Full fire engulfment
  - Thermal coating: 6 mm intumescent coating (used in BAM test)

Calculation Number	6	7	8	9
Volume (m^3)	30	30	60	60
Safety Valve	No	Yes	No	Yes
Intumescent coating	Yes	Yes	Yes	Yes

- The following figure shows results obtained by INERIS



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Conclusion

- Comparison BAM tests vs. INERIS model complete
  - Model results in accordance with test measures
  - Reliability of the model with safety valves and thermal coatings
- The model has been used to study 2 common tank configurations (31 & 60m^3), equipped with common safety valves and/or thermal coatings
- Results show that both protection measures may delay or avoid a BLEVE
  - Calculations are now led by INERIS to optimize the thermal coating thickness
  - An objective in terms of thermal insulation (i.e. thermal resistance) could be defined whatever the coating technology
- However safety valves are not efficient for some fire scenarios
  - The safety valve is directly impacted by the heat input (cf. BAM Tests)
  - Considering current conception standards (ex : ASME), the failure pressure (decreased by the heat load) can be lower than the opening safety valve pressure

Way forward

- The advantage of a theoretical model is that it allows to test a big number of possible cases at a lower cost than tests
- The simulation presented above have been done to illustrate the possibilities of the model
- The joint meeting is invited to comment on this procedure and consider a list of case that would be necessary to verify in order to get enough information for decision making
- Experimental tests may be necessary
  - To investigate the mechanical response of safety valves under thermal loads (insulation material to protect the safety valve?)
  - To get an ultimate verification by test