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EXPANDED ALUMINUM and BLEVE

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October, 23th 2019

IMT Mines Alès
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- Responsible of the *Spark experimental facility* (500 m^2; fire and explosion facility)

CONTENT OF THE PRESENTATION

What is and what is not a BLEVE ?

Accidents involving a fireball are not necessary BLEVE

True BLEVE (LPG)

Strong blast
Fragments (heavy, far)
Huge fireball

Partial rupture of the vessel (LPG)

Medium blast
No or little fragments
Fireball or jet fire (longer)

Partial or total rupture of the vessel (diesel)

Medium or weak blast
Fragments in a narrow range
Huge fireball

What is and what is not a BLEVE ?

BLEVE potentially occurs when three conditions are reached:

- The liquid phase is highly superheated

$$T_{rupture} >= T_{superheat\ limit}$$

Typical value of superheat limit are:

Propane:	$T_{superheat\ limit}$	~ 50°C
Water:	$T_{superheat\ limit}$	~ 300°C
Octane:	$T_{superheat\ limit}$	~ 200°C

- The liquid phase vaporizes at high velocity

- The container has to be pushed far away it's nominal resistance at the time of vessel rupture

For weak tanks (atmospheric vessels) and high superheated state, there is a low probability of BLEVE

SUMMARY

BLEVE is a serious event. Compared to fuel tanker explosions, effects are increased by the high superheated state and very rapid boiling :

- By adding energy to blast effects (multiple blasts)
- By providing massive kinetic energy to fragments
- It provides a massive force on the ground

◀ Bologna bridge collapse would probably not have occurred with a fuel tanker explosion

▼ What about Millau bridge ?

Expanded aluminum filling

Expanded aluminum benefits

Birk et al (2008)[1] performed a detailed analysis of aluminum products benefits and problems.

First products appeared in the late 1970s and were demonstrated to be efficient for:

- Fuel-air explosions severity explosion in closed spaces
- Flame arresters
- Sloshing reduction
- Static electricity dissipation
- Evaporation reduction

Some benefits are questionable:

- Projectiles impacts. *Copland at al (1983)[2] demonstrated inexistent or negative effects of EA in tanks impacted by a projectile*
- Condensation of vapors. *No scientific evidence of this benefit*

[1] Birk, AM, 2008, *Review of expanded aluminum products for explosion suppression in containers holding flammable liquids and gases*, Journal of Loss Prevention in the Process Industries

[2] *Copland, A. (1983), Hydraulic ram attenuation, ARBRL-MR-03246*

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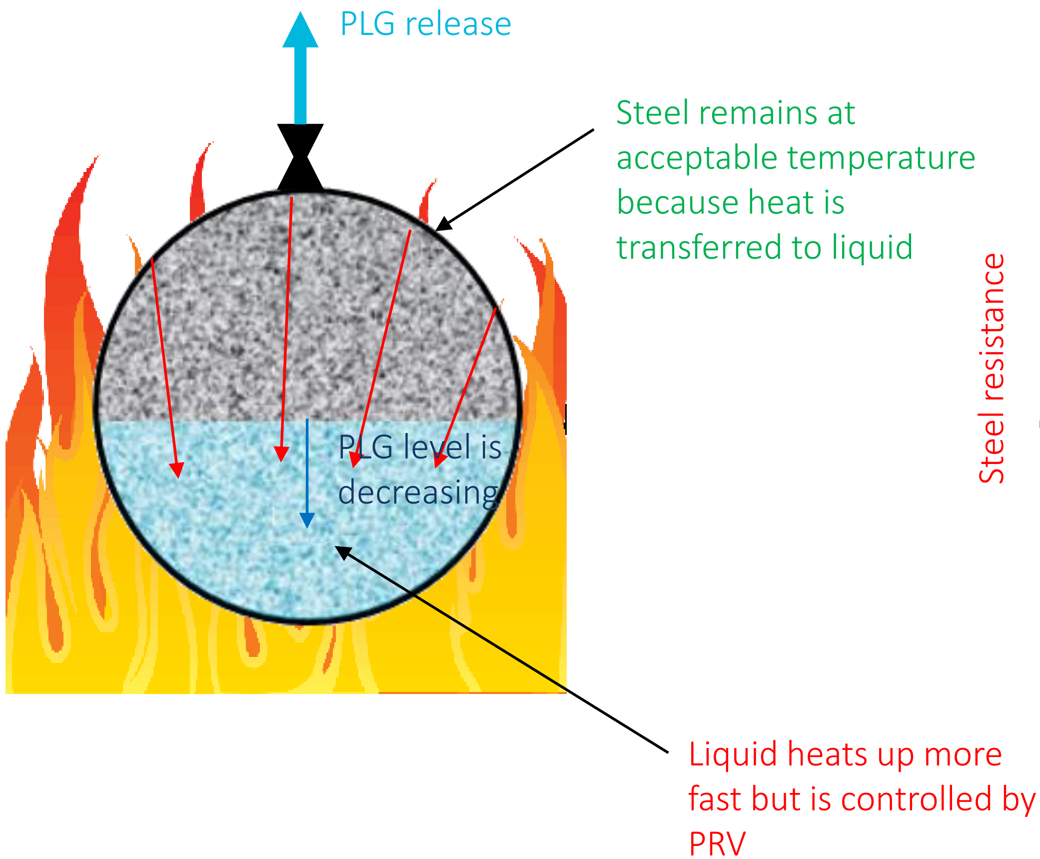
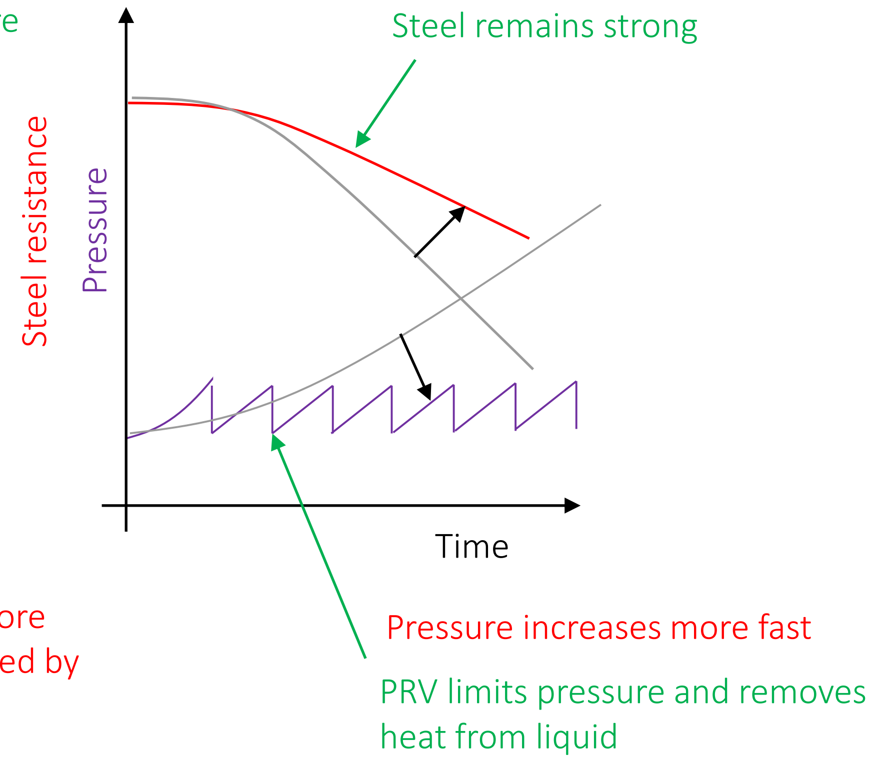
Expanded aluminum and BLEVE

CLAIM 1 : EA will suppress BLEVE because it keeps wall temperature at reasonable temperature





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PLG = pressure liquefied gas / EA = expanded aluminum / PRV = pressure relief valve

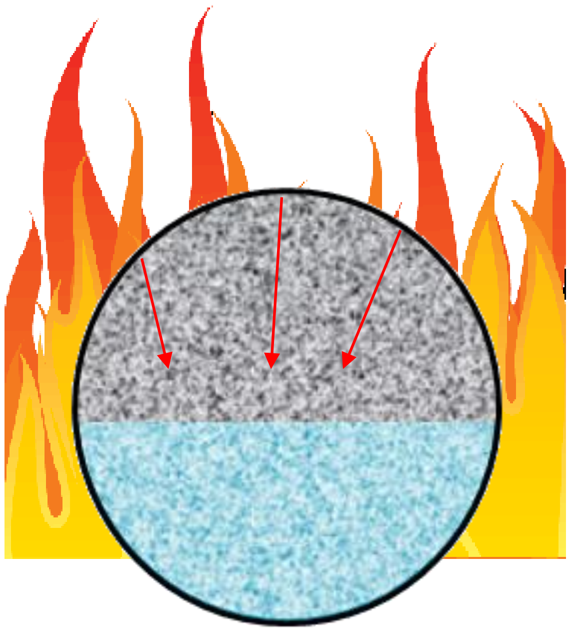
Expanded aluminum and BLEVE

Conclusions about CLAIM 1

- *The physical principle of EA seems good; a PRV valve is however required to control pressure increase and to release energy*
- *If no PRV is installed; no physical reason may exclude BLEVE if fire continues*
- *If no PRV is installed; it is not clear if BLEVE will occur before or later.*

Expanded aluminum and BLEVE

CLAIM 2 : EA will suppress BLEVE because it transfers heat to the vapor phase



- Yes, high thermal conductivity and large surface of EA in contact with vapor increase heat flux transferred to vapor
- Vapor has little heat capacity and will absorb little heat
- It can be expected little efficiency to cool wall by transferring heat to vapor phase

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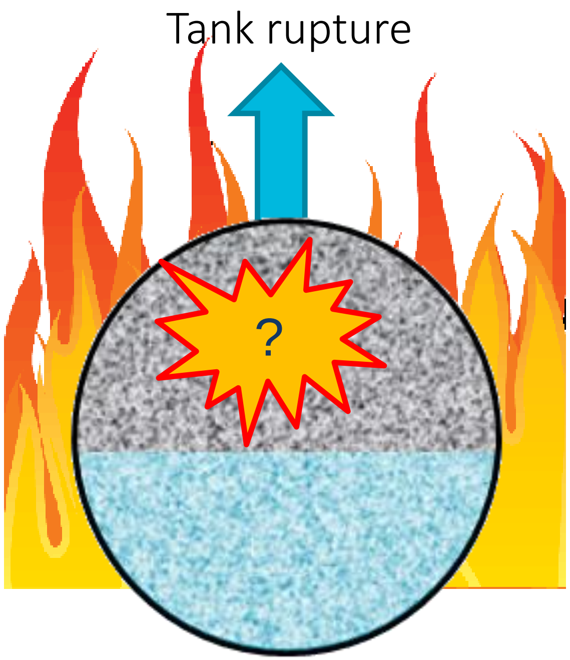
Expanded aluminum and BLEVE

CLAIM 3 : EA will suppress BLEVE because of its anti-explosion properties



- Chemical explosion in the vessel:

At rupture time, there is no risk of internal explosion due to PLG explosion (no oxygen). No evidence that a chemical explosion could happen in the vessel

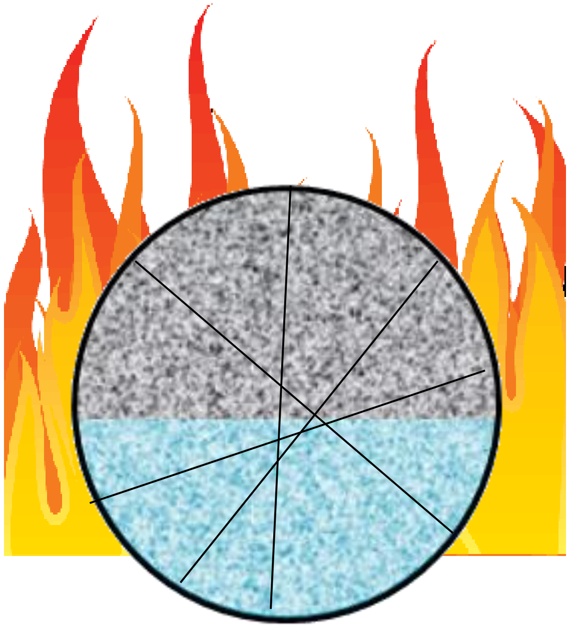
For flammable liquids it depends if the vapor space is ATEX zone

- Physical explosion in the vessel:

For superheated liquids, phase change dynamics (boiling velocity) will certainly be affected by EA, but how ?

Expanded aluminum and BLEVE

CLAIM 4 : EA will reinforce the mechanical structure of the vessel



- *EA is not fixed at the wall*
- *EA foils have low tensile strength*

Previous studies and results

Several works were performed before:

- Appleyard (1980)
- Venart (1985)
- Caumont (2007)
- Heymes (2007)

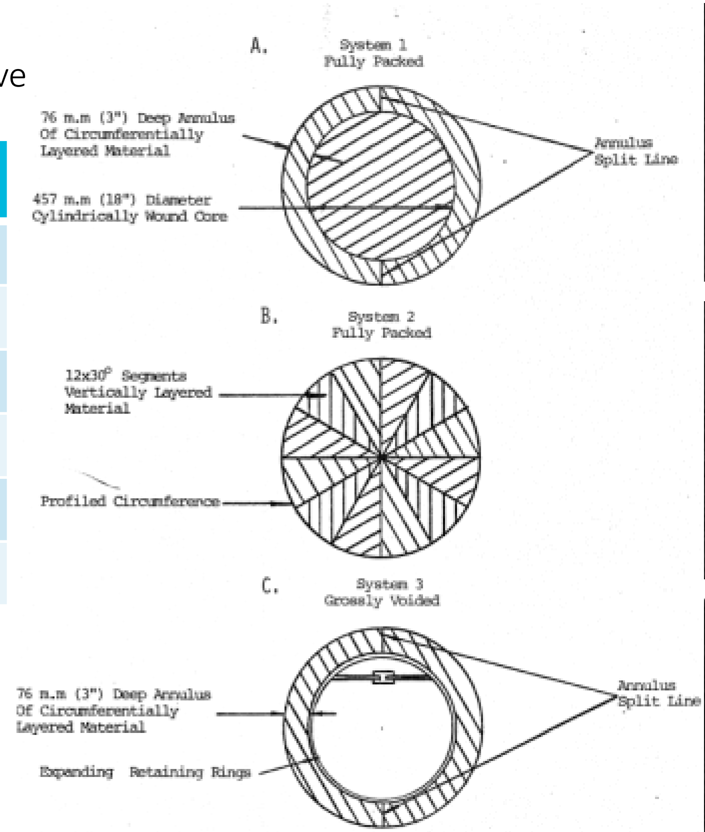
Appleyard, 1980

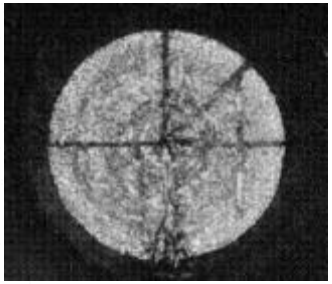
In 1980, a series of tests was funded by Transport Canada to test EA provided by Explosafe.

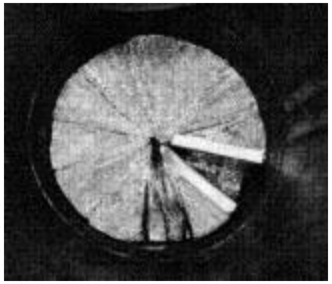
- Tests considered 6 tanks (980L) representing 1/5 scale of real 125 m^3 rail cars
- Tanks were filled with 85% propane
- Fire scenario was pool fire of JP4 fuel
- Tanks were equipped with a pressure relief valve

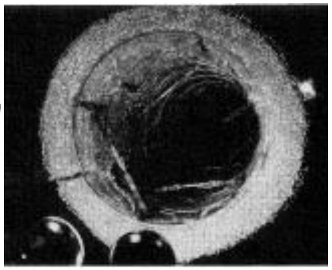
Test	Name	EA filling
1 (a)	BASELINE	None
2 (b)	DRES SPECIAL	System #1
3	HOWLER	System #2
4	NOVA	System #3
5	DIABLO	System #1
6	ENIGMA	None

(a) No data
(b) Fire problems




System #1


System #2


System #3

Appleyard, description of tests outcome

BASELINE test (without EA) resulted in a loss of containment, maybe a BLEVE

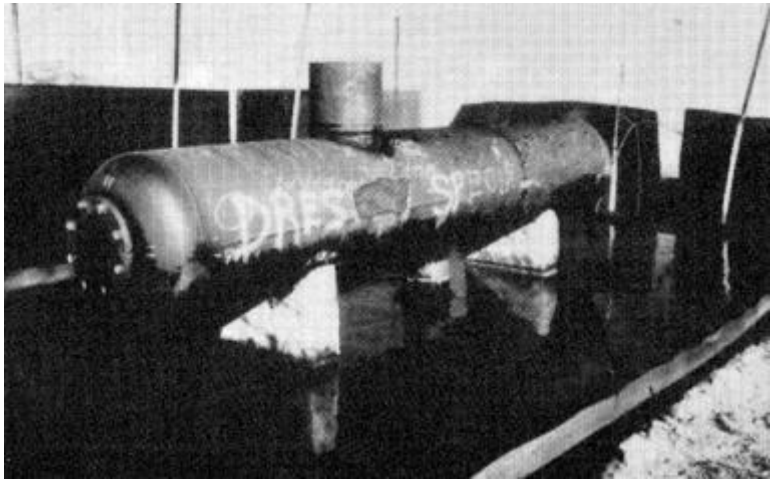
Pool fire test and pressure valve open

Half of the vessel was splayed of

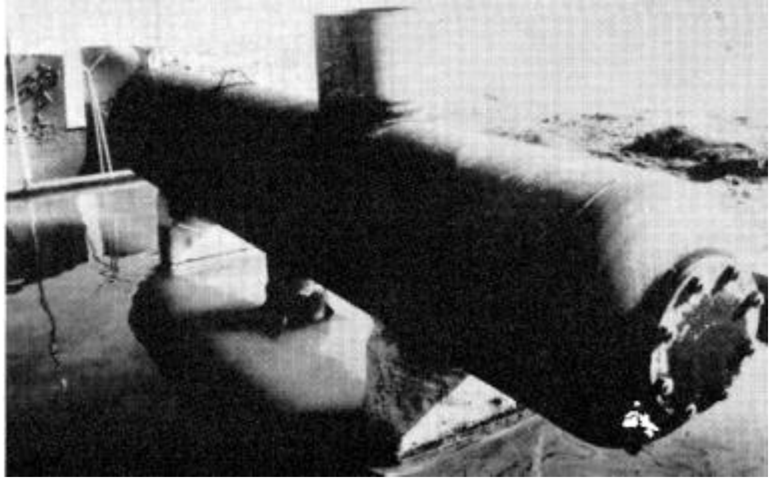
- Loss of containment in 10 min
- Venting started at 2 min
- Relief valve was still working after the test
- Venting flame was very high
- Fire pan was destroyed
- No data because of technical failure of sensors connections
- Temperature 0°C ; wind 12 km/h

Appleyard, description of tests outcome

DRES SPECIAL (with EA) remained safe



DRES SPECIAL vessel after test



- DRES SPECIAL remained safe
- No apparent damage to the tank

- Venting started at 2 min 30
- Tank vented safely propane and was empty in 15 min
- Pressure valve was still working after test

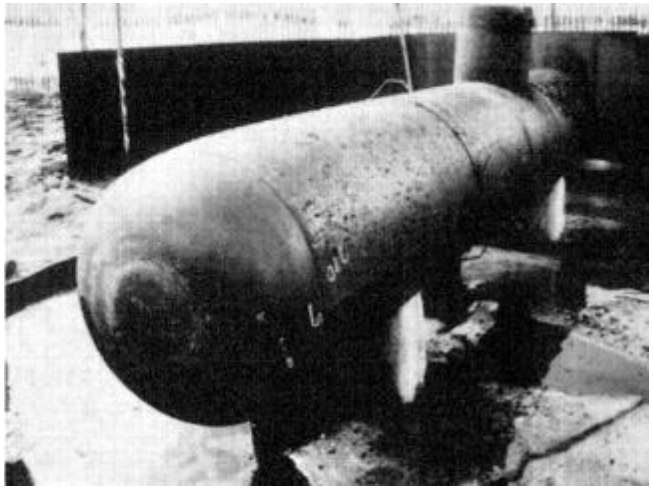
- Fire problems (lack of fuel)

- Max. wall temperature (630°C)
- Estimate average heat flux 64.2 kW/m^2

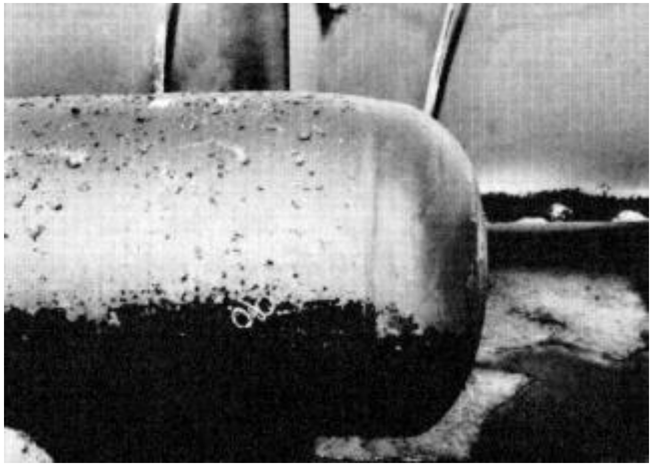
- Very cold conditions
- Temperature -22°C ; wind 10 km/h

Appleyard, description of tests outcome

HOWLER (with EA) remained safe



HOWLER vessel after test, a bulge appeared



- HOWLER remained safe
- A significant bulge was observed on one end

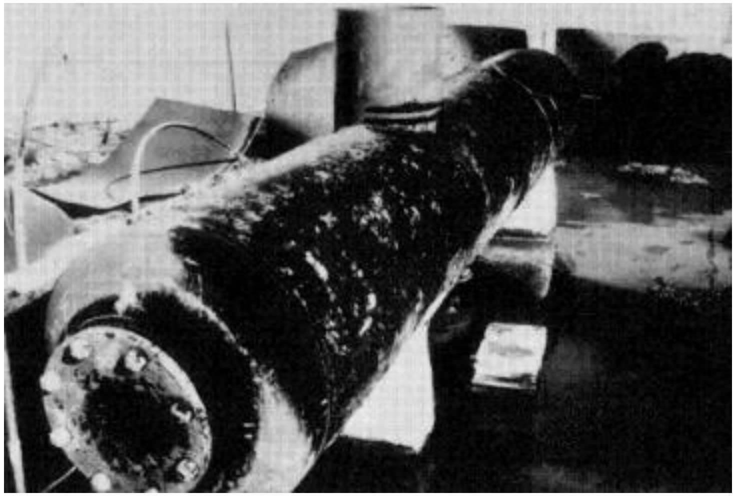
- Venting started at 2 min
- Tank vented safely propane and was empty in 15 min
- Pressure valve was still working after test

- Very high max. wall temperature (710°C)
- Peak pressure 17 bar
- Approx. av. fire temperature 770°C
- Estimate average heat flux 52.1kW/m^2

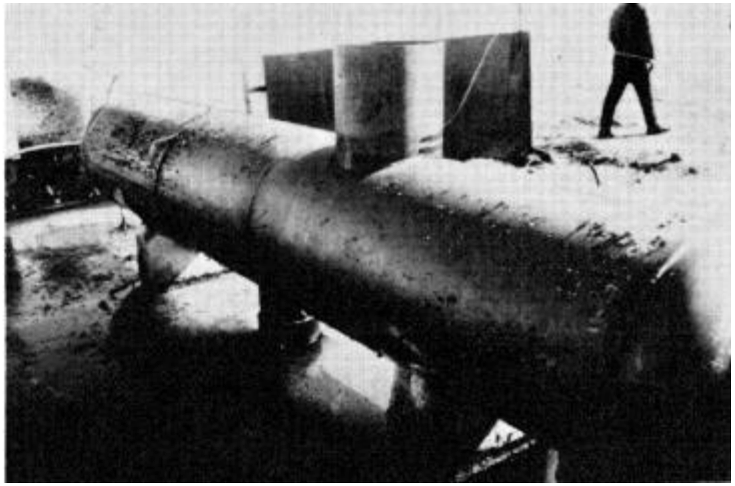
- Temperature -7°C ; wind 11 km/h

Appleyard, description of tests outcome

NOVA (with EA) remained safe



NOVA vessel after test



- NOVA remained safe

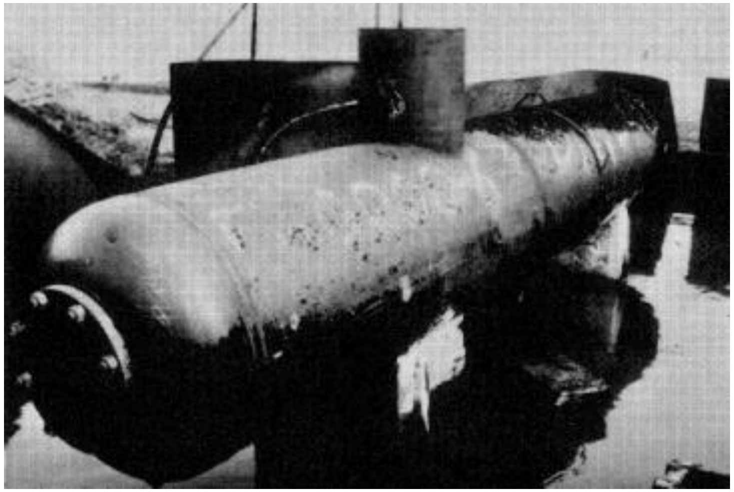
- Venting started at 2 min
- Tank vented safely propane and was empty in 15 min
- Pressure valve was still working after test

- Max. wall temperature (630°C)
- Peak pressure 16 bar
- Approx. av. fire temperature 650°C
- Estimate average heat flux 29.1 kW/m^2

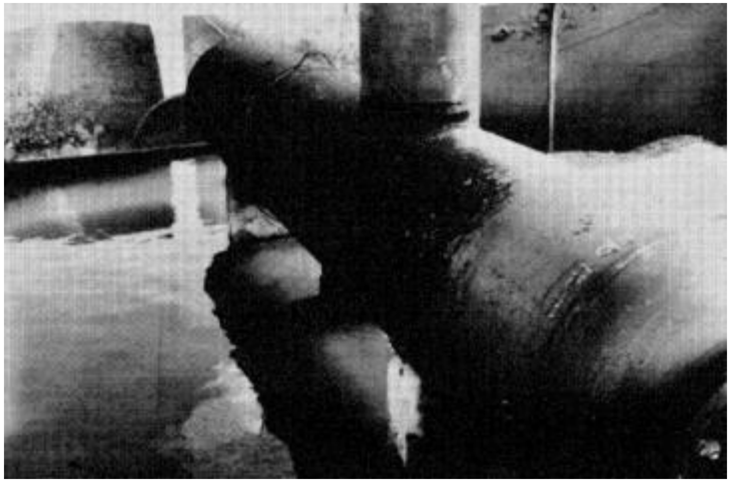
- Temperature -2°C ; wind 4 km/h

Appleyard, description of tests outcome

DIABLO (with EA, repeat of DRES SPECIAL)



DIABLO vessel after test



- DIABLO remained safe

- Venting started at 2 min
- Tank vented safely propane and was empty at 15 min
- Pressure valve was still working after test

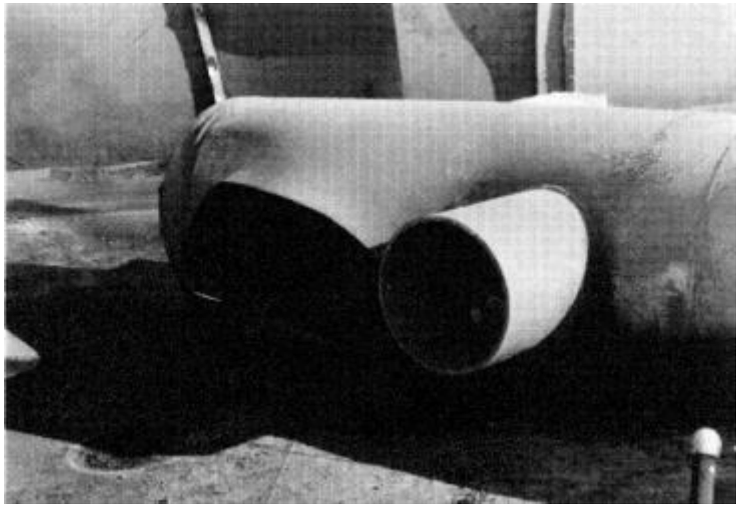
- Max. wall temperature (590°C)
- Peak pressure 20 bar
- Approx. av. fire temperature 780°C start; 630°C end
- Estimate average heat flux 50.3 kW/m^2

- Temperature -3°C ; wind 15 km/h

Appleyard, description of tests outcome

ENIGMA (without EA, repeat of BASELINE)

ENIGMA vessel after test

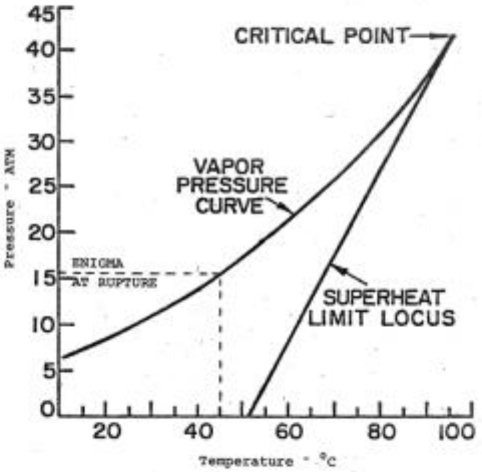


- Loss of containment at 7.5 min

- Venting started at 2 min
- Relief valve was still working after the test
- Venting flame very high

- Max. wall temperature (570°C)
- Peak pressure 19 bar
- Approx. av. fire temperature 700°C
- Estimate average heat flux 45.9 kW/m^2

- Temperature 0°C ; wind 3 km/h



Conclusions by the authors (Appleyard)

- Tests outcome is obvious: tanks without EA exploded; tanks with EA remained safe
- Even if heat fluxes were estimated as low; fire was considered as severe
- Authors admit that fire was too poorly characterized and was not consistent from test to test
- Two systems of EA (#1 and #3) appeared effective in maintaining vapor space wall temperatures below critical levels
- Complete filling of the vessel with EA is not essential
- Intimate contact between EA and wall is essential

Conclusions by an external analysis

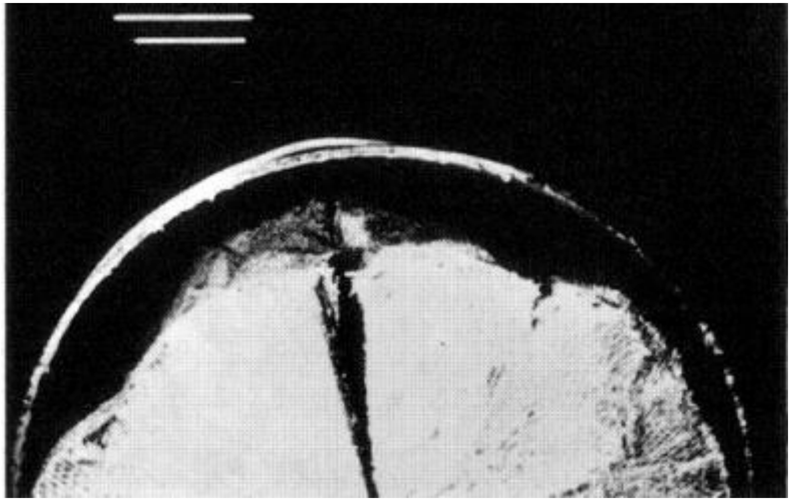
The outcome of the tests could not be clearly attributed to the EA

Dr AM Birk

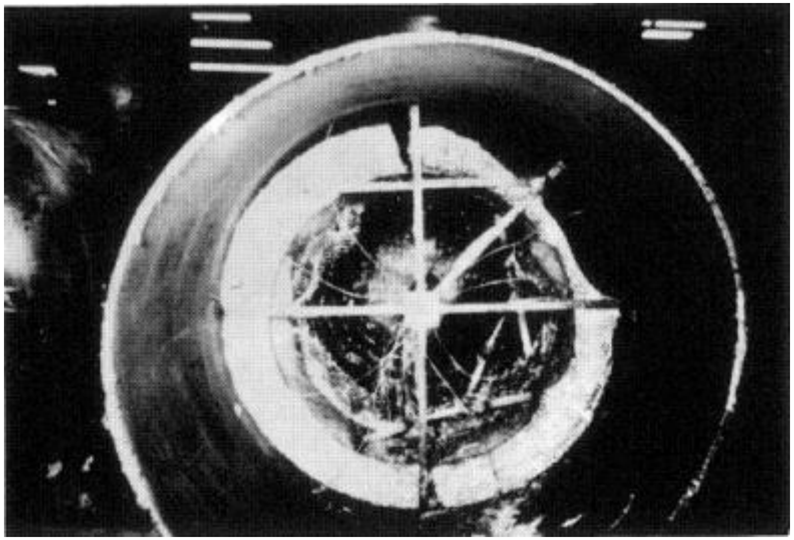
- Pool fire are really tricky to control. Dr Birk performed many BLEVE tests with pool fires and observed tanks that survived severe fire conditions without thermal rupture (and no EA)
- Pool fires of Appleyard were not severe. The measured fire temperatures from the tests allows to eliminate three of the four EA equipped tests due to low or decreasing fire temperatures during the tests. ;None of the tests come close to meeting the fire testing standard of US Code of Federal Regulations
- Pool fire of Appleyard were not consistent and not reliable. During a test, a difference of 200°C was observed between two different points in peak wall temperature; comparing tests the fire test conditions were different for the four tests
- Pressure relief valves didn't open at the same pressure and softened differently during the tests. Howler was saved thanks to the valve spring softening
- By comparing Enigma and Diablo, no difference in wall peak temperature was observed during the first 4 minutes. Why ?
- Why do Howler experienced had a peak wall temperature of 710°C ? Why there was no failure ? (Enigma failed at 560°C)

Supplementary comments by Heymes

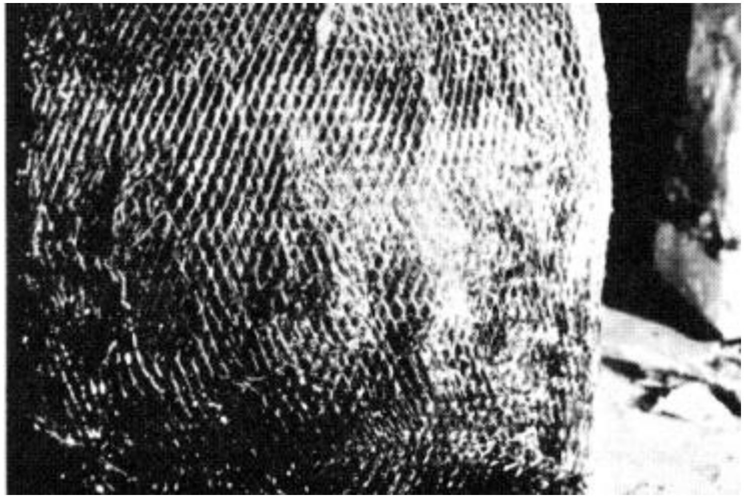
- Pictures of EA after testing show a collapse of EA during the test. It is not clear if it is due to aluminum weakening when heating or to propane relief through pressure valve
- Aluminum melted in Diablo test



System #2, Howler



System #3, Nova



System #1, Diablo

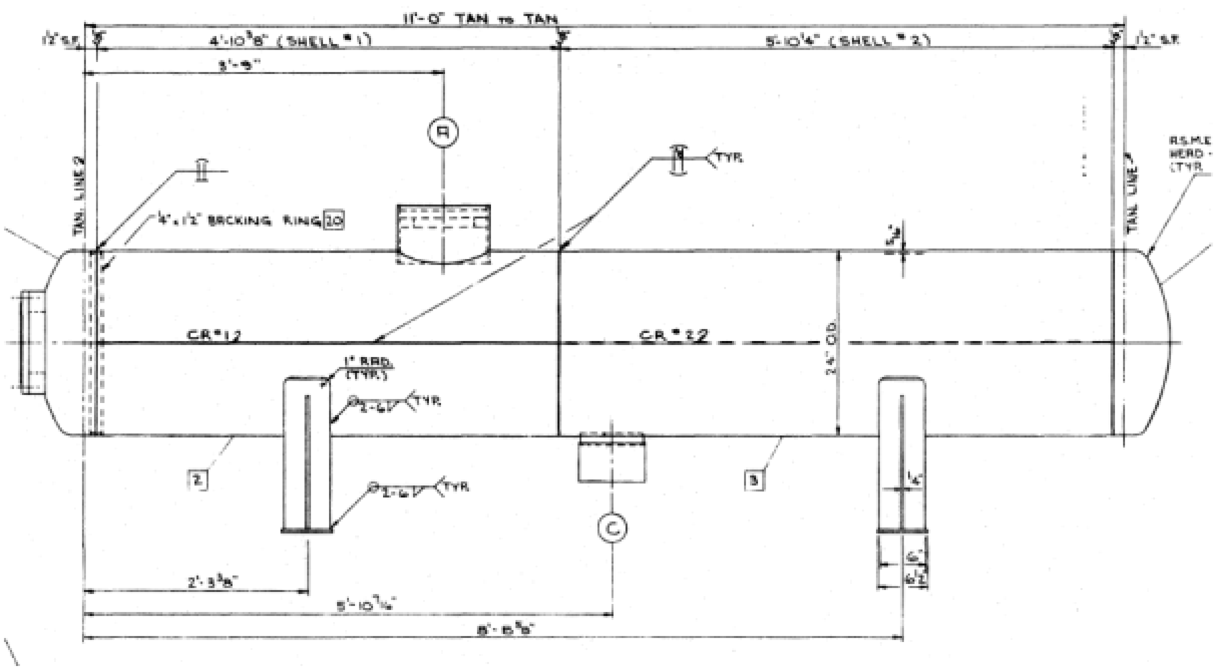
Supplementary comments by Heymes

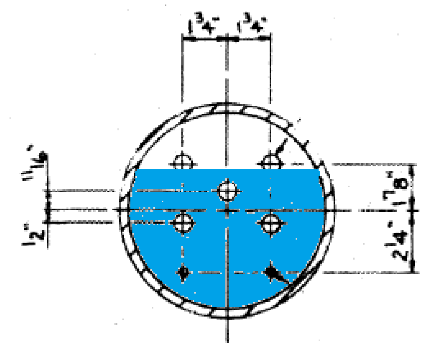
- Scale effect may have significant influence on results.
  - Diameter was very small (60 cm), liquid level was high

$$\varphi = -k\frac{\Delta T}{\Delta x}$$

For a same ΔT; heat flux transferred by EA decreases with tank increasing diameter and decreasing filling level

  - Size of EA is not scaled down compared to tank dimensions



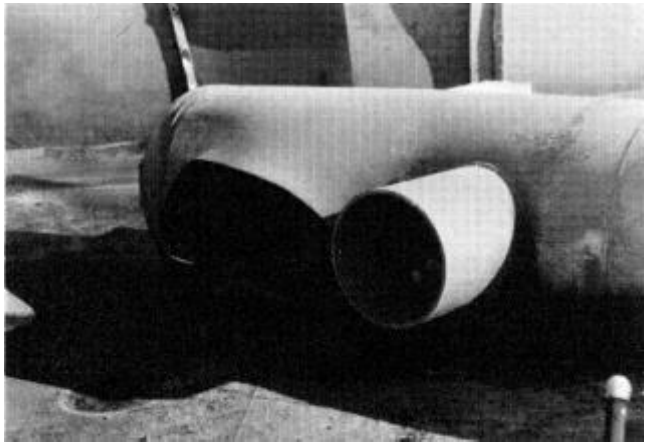


Supplementary comments by Heymes

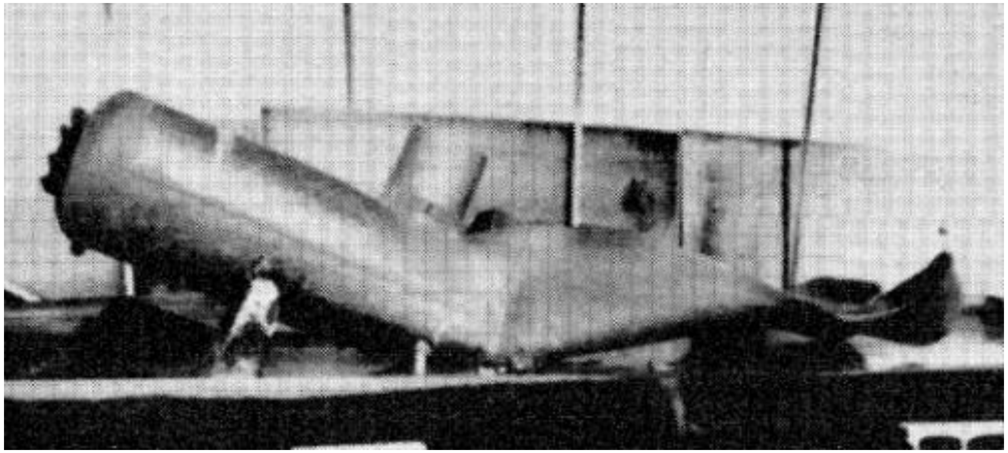
- Failing tests were probably not true BLEVE. Maybe without EA they would have worst consequences. It seems that BASELINE and ENIGMA failed without fragments and probably a lower blast.

- It would have been nice to have data from some blast sensors

Enigma



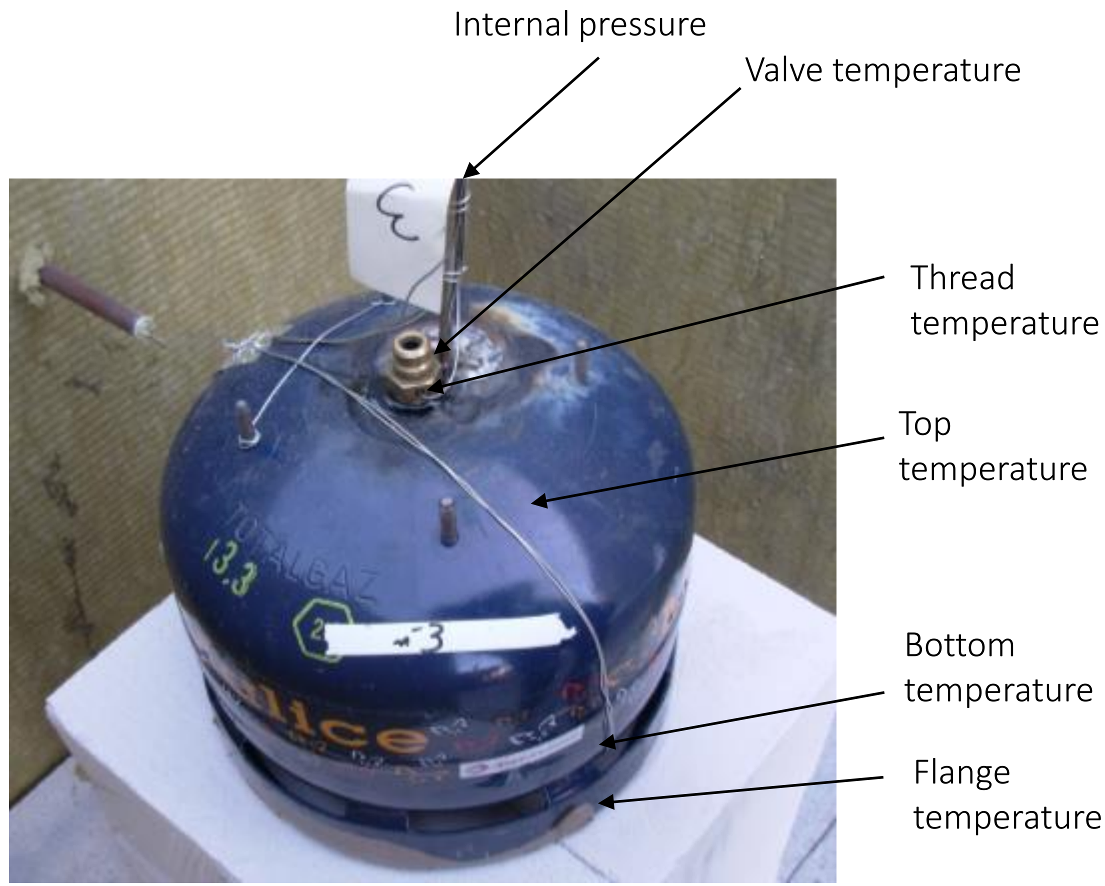
Howler



Caumont, 2007

An experimental work was performed at GESIP facility with 6 kg cylinders filled with butane

- Heating by propane burners according to ISO834 standard
- No pressure valve
- Two cylinders were filled with aluminum balls (Balls Al / Ti; diameter 20 mm ; Apparent density 54 g/L)



Caumont, 2007

Results and discussion

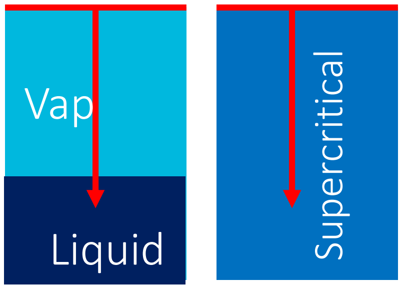
Test	Load	EA filling	Outcome	Rupture pressure	Top temperature	Liquid temperature
1	Full 6 kg butane	0%	BLEVE at 6 min 31	80.4 bar	365°C	66°C
2	Full 6 kg butane	100% 662g EA	BLEVE at 5 min 52	83.5 bar	334°C	52°C
3	50% full 3 kg butane	0%	Partial rupture at 6 min 51	51.2 bar	597°C	70°C
4	50% full 3 kg butane	100% 656 g EA	BLEVE at 7 min 02	51.7 bar	526°C	78°C

Results show that peak temperature was decreased by 30-50°C for cylinders with EA

Caumont, 2007

Conclusions

- All cylinders failed after 6-7 min
- EA didn't avoid BLEVE
- No BLEVE without EA (test 3)
- Top wall was slightly cooler with EA (decrease of 30 - 70°C)
- No conclusion about liquid temperature increase



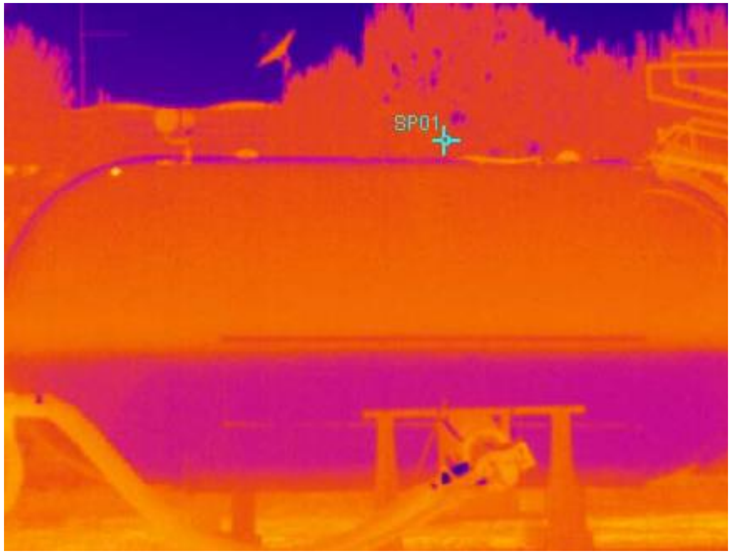
1/ These tests doesn't demonstrate efficiency of EA in 6 kg cylinders to prevent BLEVE

2/ Careful because butane is in supercritical phase at 80 bar and there is no liquid phase, therefore it's a different heat transfer process

Heymes, 2007

Large scale tests

Objective: Thermal study of tanks exposed to fire
Comparative test with / without EA
Filled with water
Large set of temperature measurements



- 22 m^3 tank, equipped with a PRV set at 3 bar
- Jet fire tests
- Different fillings with EA: hanks; balls
- Filling with water

Heymes, 2007

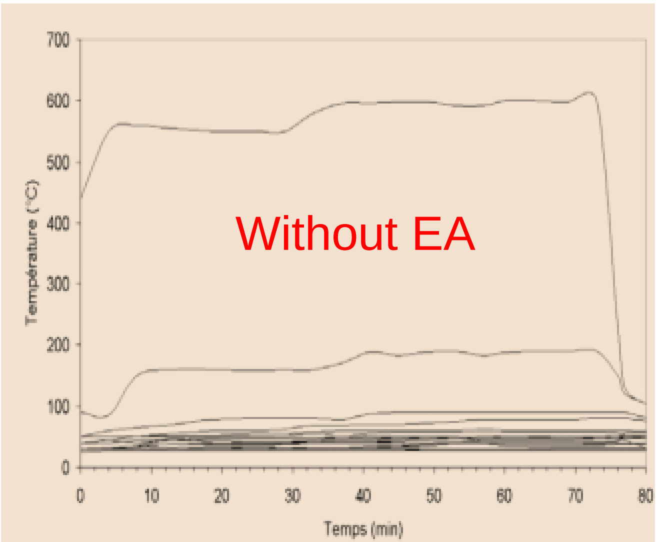
Results and discussion

Test	Fire	Objective	EA	Jet fire fuel flowrate	Filling	Max wall temperature	Duration
#5	Jet fire	comparative thermal study	Empty	0.64 kg/s	30% water	600°C	78 min
#6	Jet fire		Hanks	0.69 kg/s	30% water	600°C	72 min

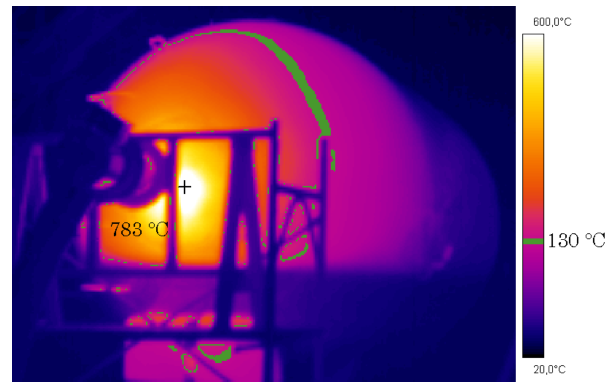
Heymes, F; (2015) *Experimental study of expanded aluminum products efficiency for BLEVE suppression*, Chemical Engineering Transactions, vol 43, 2095-2100

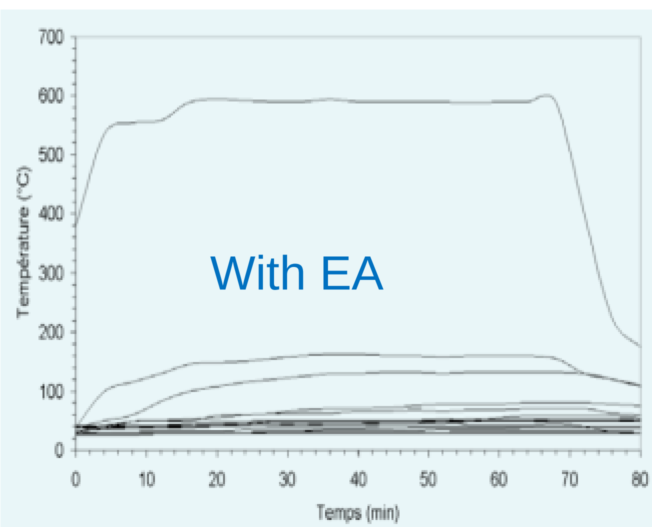
Heymes, 2007

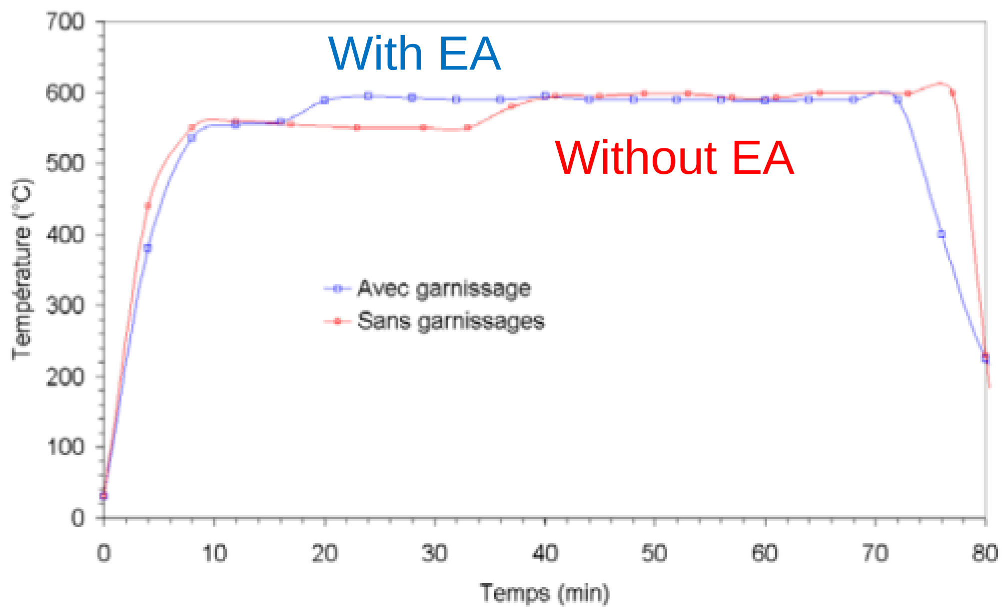
Wall temperature (internal)



Comparison of max wall temperature
(located at jet fire position, internal face)

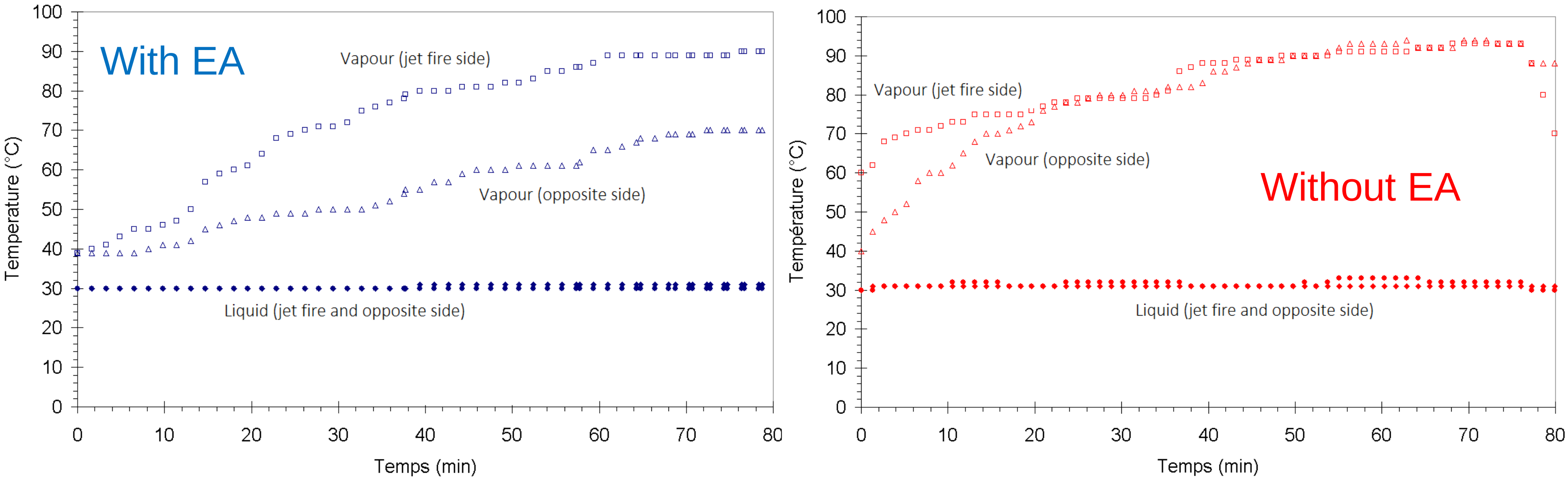






Heymes, 2007

Liquid and vapor temperature



Conclusions:

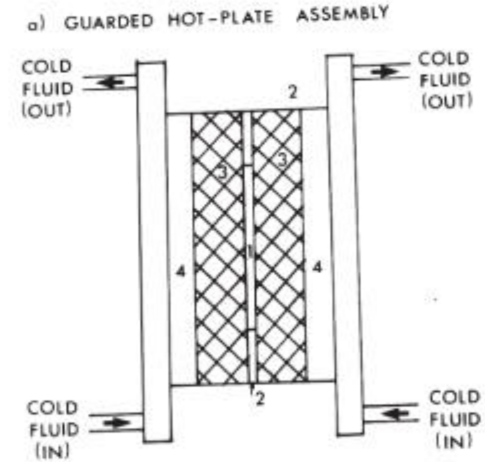
- Wall temperature was very high and identical for the two tests: no influence of EA
- No significant heat transfer to liquid and vapor phase
- EA seems to have reduced free convection in the vapor phase

Heymes (2007) and Venart (1985)

Small scale study on heat transfer capacity of EA

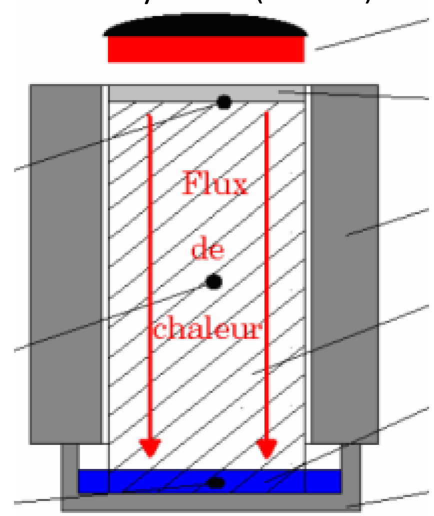
- Tests were performed to investigate heat transfer efficiency of EA
- Transfer is mostly achieved by conduction (convection is reduced; radiation is reflected)

Configuration	Thermal conductivity	
	Heymes	Venart
Hanks #1	0.774 $W.m^{-1}.K^{-1}$	0.450 $W.m^{-1}.K^{-1}$
Hanks #2	0.074 $W.m^{-1}.K^{-1}$	0.200 $W.m^{-1}.K^{-1}$
Balls	0.102 $W.m^{-1}.K^{-1}$	---



Venart (1985)

Heymes (2007)



Hanks #1

Balls

Hanks #2

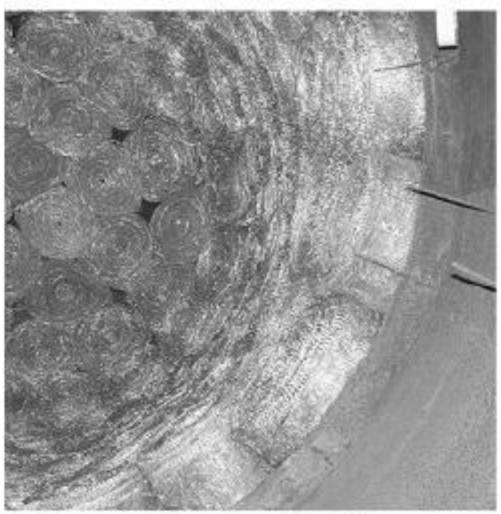
Heymes (2007) and Venart (1985)

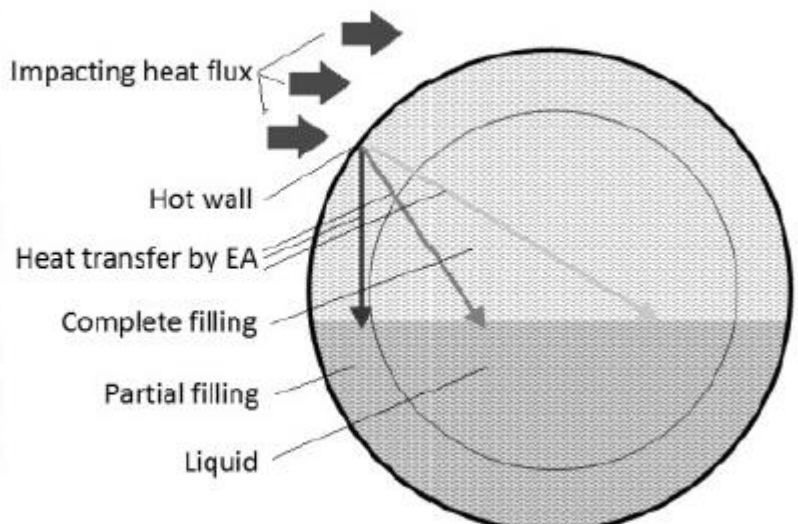
Conclusions

- EA has limited heat transfer capacity by conduction
- It has to be added the contact resistance at wall, major problem
- EA is expected to reduce heat transfer by convection and radiation in vapor phase
- EA will influence thermal stratification in liquid phase
- Thermal conductivity of steel is approx. 40 $W.m^{-1}.K^{-1}$

Configuration	Apparent thermal conductivity	
	Heymes	Venart
Hanks #1	0.774 $W.m^{-1}.K^{-1}$	0.450 $W.m^{-1}.K^{-1}$
Hanks #2	0.074 $W.m^{-1}.K^{-1}$	0.200 $W.m^{-1}.K^{-1}$
Balls	0.102 $W.m^{-1}.K^{-1}$	---

- Considering only efficiency of heat transfer to the liquid phase, the worse scenario is a low filling in the tank


Internal view of partial filling with hanks



Techno kontrol tests

TechnoKontrol™
WHERE YOUR SAFETY IS OUR PRIORITY

Comments about techno-kontrol tests

Techno Kontrol tests demonstrates clearly that no explosion occurred during a long time pool fire:

- At two different scales for LPG
- At large scale for diesel
- Tests show the ideal outcome of a tank engulfed in fire : pressure valve opens, limits pressure, removes energy, keep pressure below rupture point and no loss of containment until tank is empty

However, it doesn't prove that EA saved the tanks:

- No comparative tests with / without EA
- No data about fire severity
- Maybe the pressure valves were just working perfectly ?
- No experimental data about max wall temperature (no IR data please)
- 50% filling is not necessary the worst case

Main conclusions about all studies

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Main conclusions about all studies

BLEVE suppression

- Some data seem to show that EA is efficient to avoid BLEVE
- Some data seem to show that EA is not efficient
- Even if 3 large scale testing campaigns were undertaken, no one gives certainty

Practical issues

What happens if:

- After several month of use, EA settles down and contact with steel surface is lost;
- EA blocks pressure relief valve during relief ?

Influence on BLEVE severity

If EA fails preventing BLEVE, what about the consequences ? (See tricky points)

- Blast could be increased / reduced
- Fragments could get more / less kinetic energy
- Fireball could be less/ more intense

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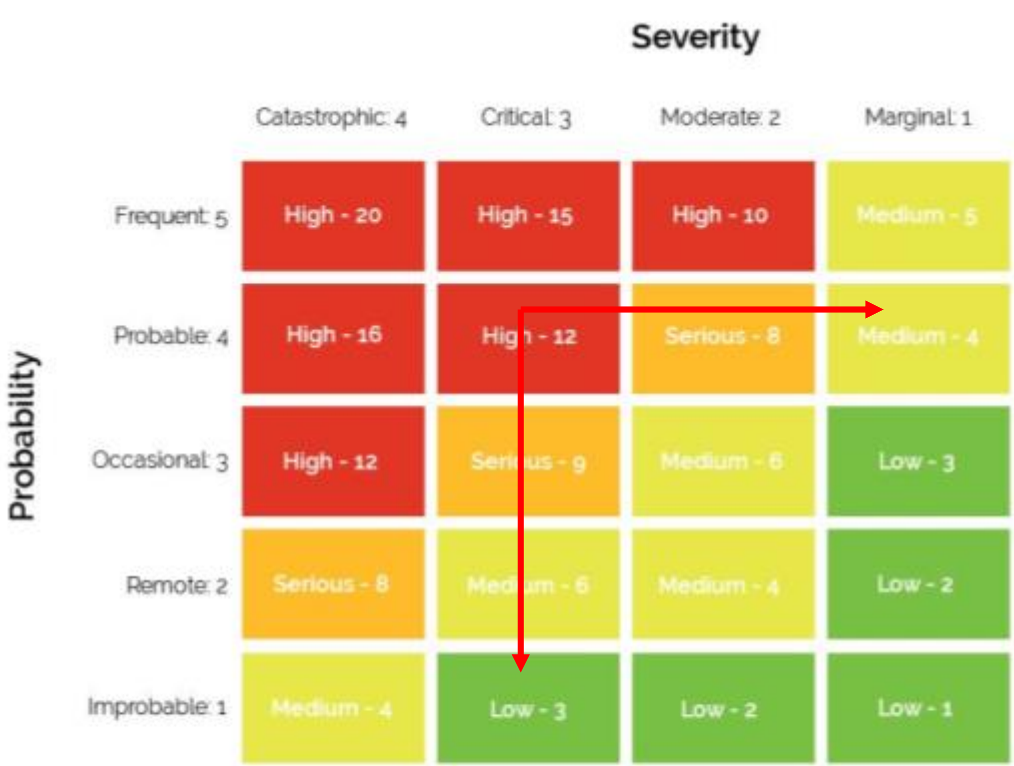
Another way to consider EA

All previous tests aimed to decrease probability of BLEVE. But maybe EA reduces severity

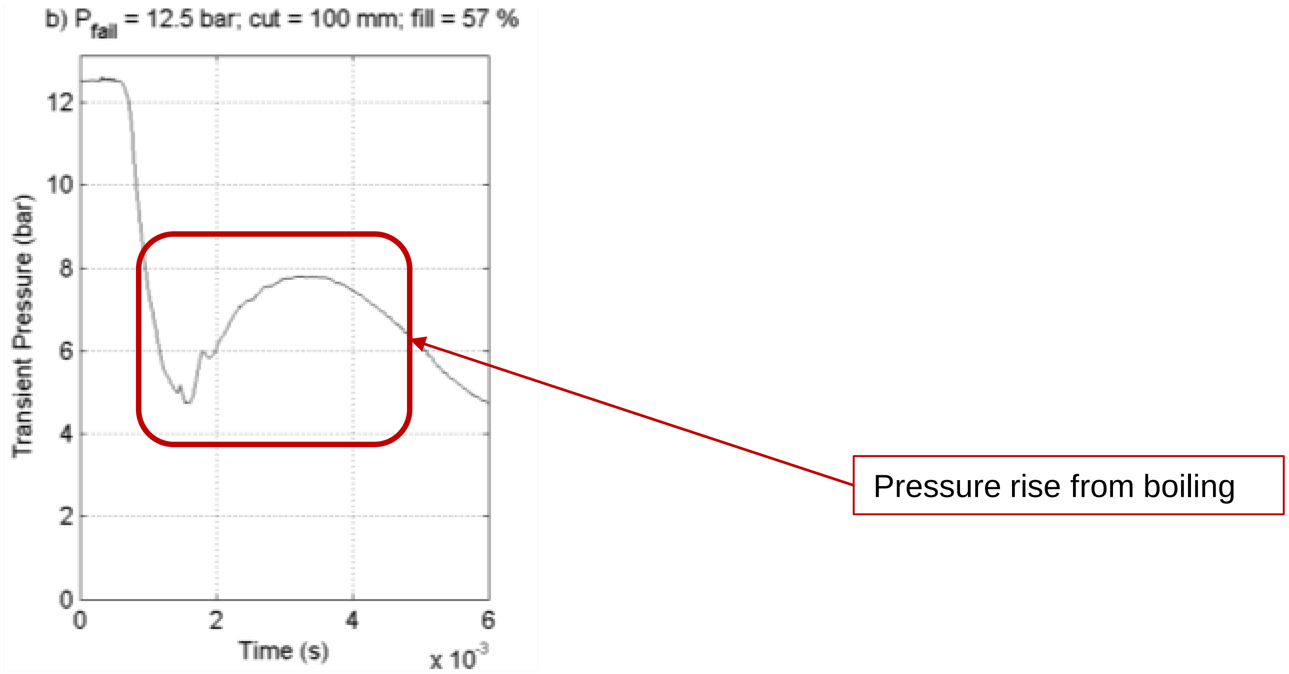
- Efficient even without PRV
- Efficient even if truck is overturned



Tricky points

SPECIFIC POINTS

1. Explosive phase change depends
- on the depressurization velocity (No BLEVE triggered by pressure relief valve)



EA could reduce BLEVE severity by slowing pressure drop in the vessel

SPECIFIC POINTS

2. Explosive phase change depends
- on the nucleation sites in the vessel (wall, impurities)

EA is a fantastic promotor of nucleation sites, this could increase BLEVE power

SPECIFIC POINTS

3. Explosive phase change depends

- on the flash fraction

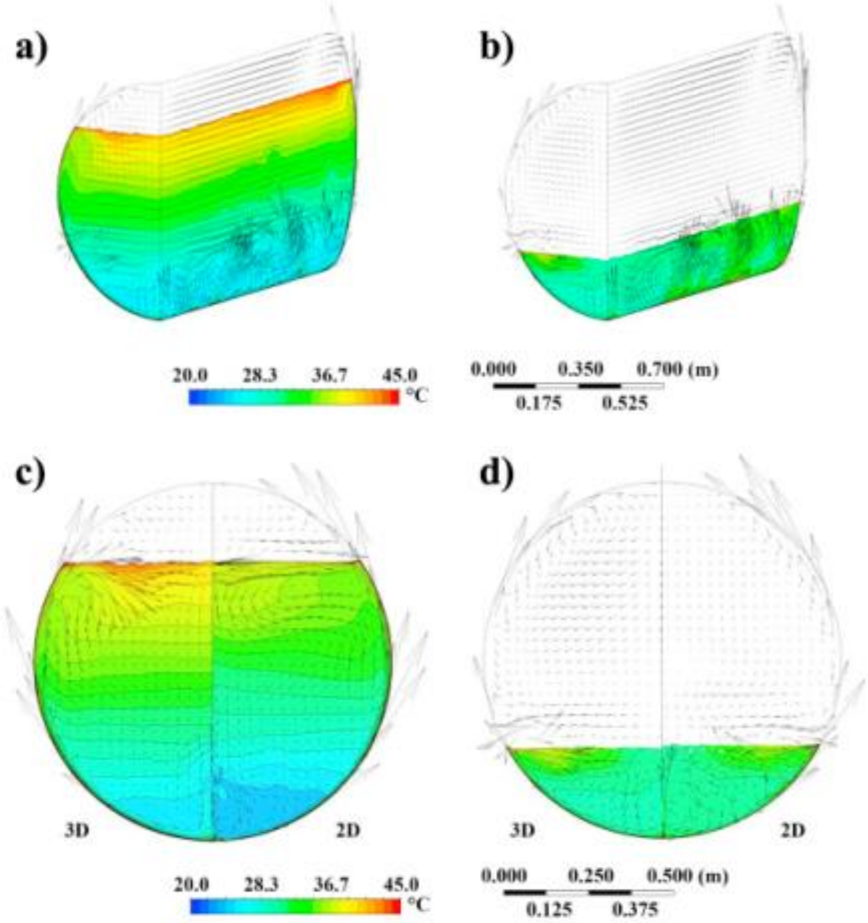
EA stores heat before rupture; at explosive boiling step this heat will contribute to increase flash fraction and therefore vapor volume.

It may be expected a worse blast

SPECIFIC POINTS

4. Liquid is thermally stratified in large vessels and high filling levels exposed to fire

If EA kills stratification, pressure will increase more slowly. But at the time of rupture more energy will be stored in the liquid phase



SPECIFIC POINTS

5. Aluminum combustion is highly exothermic

Il EA kills stratification, pressure will increase more slowly. But at the time of rupture more energy will be stored in the liquid phase

What happens in the fireball with EA ? Will the heat flux increase ?