UN/SCETDG/58/INF.38

**Committee of Experts on the Transport of Dangerous Goods
and on the Globally Harmonized System of Classification
and Labelling of Chemicals**

25 June 2021

Sub-Committee of Experts on the Transport of Dangerous Goods

Fifty-eighth session
Geneva, 28 June-2 July 2021
Item 5 (c) of the provisional agenda
Transport of gases: miscellaneous

Report of the intersessional working group on the pV-product limit for pressure receptacles

Transmitted by Chair of the informal working group

1. The working group met twice under the chairmanship of Dr. Georg W. Mair (GER). The first meeting took place on 19 April 2021 from 1 to 5 p.m. Geneva time (CET). Delegates from Belgium, China, Germany, Sweden, Switzerland, United Kingdom, United States of America, CGA, EIGA and ISO joined the meeting. The delegation from Germany provided the secretary. The second meeting took place on 17 June 2021 again from 1 to 5 p.m. Geneva time (CET) with experts from Belgium, China, Germany, Sweden, United Kingdom, United States of America, CGA, ECMA, EIGA and ISO.

2. The working group considered the following documents in both meetings: ST/SG/AC.10/C.3/2020/18 with related informal documents INF.52 (ECMA) and INF.53 (GER) and the report of the last Sub-Committee of Experts ST/SG/AC.10/C.3/114.

First Meeting

3. For the first meeting the Chair drafted an agenda that was confirmed by the participants. This agenda addressed the following subjects, which are mentioned in the following items in the order of discussion.

4. To begin with, the Chair as German representative presented the basic idea of limiting the potential consequence of the transport of pressure receptacles to a non-catastrophic level. He laid the foundation as to why Germany thinks the introduction of a pV-product limit is sensible. He illustrated a model used to calculate the consequences of a sudden rupture and which critical assumptions needed to be made for that model. The numbers used in these assumptions were to be the point of discussion later on. Specifically, a number of 45 fatalities is deemed, based e.g. on Swiss regulations, the absolute maximum for any potential accident. Using population density and the propagation of a pressure wave from an explosion together with lethality limits in the model, a limit for the maximum allowed pV-product was suggested at 1.5 million bar litres. The related presentation is appended to this report as appendix 1.

5. Next, information on the general estimation of consequences caused by a sudden rupture of a pressure receptacle was communicated by the German representative Dr. Habib, who gave a detailed presentation on the model used for predicting the propagation of the pressure wave in the consequence analysis. The presentation (see appendix 2) was well received and a discussion between presenter and participants ensued. The core of this discussion revolved around the chosen Baker model and its assumptions as well as its limitations. The Chair summarised the discussion by asking if the model is overly restrictive and explaining that the new limit plays a major role to avoid routing restrictions for transports, which is a sensitive issue in a transit region like Germany. He asked all participants to come forward with alternative models and experimental as well as accidental data that could help in finding the right figure for a pV-product limitation. Some members

agreed that the pV-product is a good starting point in addressing safety issues that arise from new technologies employing pressures in the 1000 bar range.

6. Determination of a quantity for the maximum acceptable consequence

The Chair asked all participants on their opinion regarding the introduced absolute limit of 45 fatalities for any accident. To this the discussion digressed somewhat revealing that a few members were still pondering the overall necessity of any additional limitation. The Chair summed that this working group concerns road transport with volumes of pressure receptacles below 3000 litres and asked all participants to research and report their countries maximum number of fatalities tackled as a catastrophe at the limit to a major accident – or to come up with an alternative criteria for quantifying the lower border value of a catastrophe.

7. Population density to be used as reference of the estimation of consequence

The Chair asked for figures concerning the population density that the members would like to consider for the estimation of consequences. The analysis provided by Germany are based on 4000 inhabitants per square kilometre, which represents the average density of Berlin. The UK representatives acknowledged that inner city population densities would be higher than the given number but represent only a small part of the journey. Still they were uncertain which number would be correct to apply. In London the population density is 5700 inhabitants per square kilometre, outside of London it drops to 570. The Swedish representative stated that 4000 inhabitants per square kilometre is valid for Stockholm, the most densely populated area in Sweden and expressed that this figure seems to be reasonable for Sweden. The Chinese delegation calculated that all of Shanghai has a population density of 3900 inhabitants per square kilometre, but in the centre area the number goes up to around 23,000 inhabitants per square kilometre. The population distribution in cities is usually uneven, and the average density obtained by dividing the total population by the total area may not be representative. Considering the densely populated regions, China would thus prefer a number that is somewhat higher. The Belgian representative based his opinion on the population density of his hometown and concluded that, at first view, the number of the population density used in the analysis seems acceptable. The members agreed to re-check the information provided for the next meeting.

8. Determination of the critical pressure load on humans

The Chair asked the experts for their opinions on the pressure thresholds used in the consequence calculation. A representative of CGA responded that CGA has discussed the value of 2 bar over-pressure for 50% human fatality. But it has not become a CGA position. Deviations were identified between the different threshold data available to the group. It was concluded that the sources for these figures needed to be investigated and communicated for the next meeting.

9. Determination of effects resulting from splinters

The Chair communicated that splinters are not included in the current model presented from Germany and could lead to far greater consequences. One member agrees that the topic is of great importance but points out that a conservative value for the applied overpressure lethality would sufficiently represent the dangers.

10. Closing comments of the delegates at the end of the 1st meeting

At the end of the discussion the Chair gave a summary and asked each delegate for a statement on the today's meeting and further actions. Most participants expressed their gratitude for the preparation of the meeting, which provided a new view on safety aspects. A common response from many countries and parties involved was that they needed some time to study the model applied and the assumptions made for it. In many cases further experts were to be consulted before figures can be provided for the introduced approach. It was concluded that a uniformly applied pV-product limit would make room for small cylinders with very high pressures (30,000 bar for 50 litres cylinders, which is practically limited to about 1000 bars). Generally, most participants were positive to the proposal in its attempt to provide more safety for the public where there has emerged a safety gap in current regulations, allowing for pV-products that could result in an unacceptably high number of fatalities.

Second Meeting

11. For the 2nd meeting the Chair had drafted an agenda that was confirmed by the participants after having an introduction round. This agenda addressed the following parts, which are mentioned in the following items in the order of their discussion. This was supported by a presentation from the Chair provided as appendix 3. Before starting with the technical issues, the drafted report on the first meeting (para. 3 to 10 above) was checked paragraph by paragraph and agreed with some editorial modifications.

12. Discussion on pressure limits

The German BAM made an additional analysis of literature and traced relevant data back to the origin if possible. The result is provided in appendix 4. The proposal of the German delegation was to reconsider the focus on fatalities as consequence criteria and to consider insured persons in addition, both based on the already introduced Swiss regulation. This has been agreed by the group.

The proposed values for overpressure (slide 10 and 11) are 0.02 bar (injuries), 0.21 bar (high rate of injured persons and first fatalities) and 1.4 bar (99% fatalities). The slides 13 to 15 explain both extrema in considering the consequence of overpressure caused by a sudden rupture of a hydrogen pressure receptacle[1] and its physical energy. The energy of a chemical reaction of hydrogen is not considered since this consequence is estimated as less severe.

13. Consideration of injured people and fatalities in the consequence analysis

Based on the limits for overpressure the exemplary analysis of impacted persons (hydrogen, 1.5 Mio bar litres, 4000 pers./km2) shows that the number of injuries is the driving point and more critical than the number of fatalities (slide 16). On slides 17-19 the calculated ranges of consequences (horizontal beams) are compared with different severe accidents and catastrophes. China stated that a value of 45 fatalities in line with Swiss regulation would be too high. According to their regulations, 30 fatalities is the borderline from a major accident to a catastrophe, so they would prefer the maximum acceptable consequence to be determined as 30 fatalities, instead of 45(compare “Viareggio 2009” on slide 17).

14. Common determination of the reference population density

Belgium, China, Sweden and the UK provided additional values about their population densities. In most countries there is a high variety. While on the one hand some city districts go up to 6000 pers./km^2 (Sweden), 15,000 pers./km^2 (UK) or 23,000 pers./km^2 (China), on the other hand there are areas with a low density of about 0.2 pers./km^2 (Sweden). Therefore, some experts expressed their interest in considering a population density higher than the average of Berlin with about 4000 pers./km^2. Belgium expressed its wish to consider 6000 pers./km^2 (see slide 21) with reference to the density around a highly frequented road to an important harbour. The group agreed to this increase of the reference value and started to discuss possible side effects of determining such population density values. Its meaning for areas with a very high population density needs to be clarified. Each chosen value may indirectly lead to recommendations to operate in areas with a higher population density than the referenced limit exclusively pressure receptacles with a lower pV-product. A restrictive treatment of the population density will probably lead to problems in daily traffic driven routines of drivers. UK stated that for receptacles in transport ad hoc route replanning may occur due to traffic conditions and areas of high population density may be passed through even when it was not planned. CGA confirmed that ad hoc route replanning is regularly applied, and inner-city routes are used. CGA expressed its concern for adding population density to the criteria. It could encourage people to take a very narrow, localized look at the hazard. This might cause local responders to think only of their population density, addressing their immediate problem and ignoring hazards in other areas where the container might go. The requirement should be based on a credible worst-case scenario, leaving the

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[1] The maximum pressure of a sudden rupture is assumed as the maximum developed pressure, which means in case of hydrogen 118% of PW at 65°C. For other gases like CNG this value may go up to PH, i.e. 150% of PW at 65°C.

population density out. So, the group does not wish to present the reference value of the population density in its final proposal. It is just an aspect of the rationale.

15. Discussion of the pV-product

An expert representing a member company of ECMA gave a short presentation on the composite containments with a water capacity of more than 3000 litres (see appendix 5). He explained the experience with those containments that are approved in the USA under US DOT special permit. He stated that in the case of high pV-products those containments were much more robust. Due to their pressure related designs higher pressure and larger diameters required higher wall thicknesses and that this would mean a reduced risk for threats like impact, overturn and fire. There is interest in developing containments up to 160 mm wall thickness with a pV-product up to 10 Mio bar litres in the future. Therefore, the expert stated it would be better to discuss the risk including the probability for an incident instead of concentrating on the consequence in terms of a pV-limit.

The Chair thanked for this additional input. The head of delegation of ECMA stated that this presentation didn’t provide an official opinion of ECMA as this issue was still under discussion.

The Chair expressed that the task of the WG is to focus on the consequence limitation, which is – with respect to the genuine aspect of salvage pressure receptacles for pressure receptacles – necessarily linked to the pV-product. He added, there was a risk-based approach (see ISO TR 19811:2017) but the duty is to discuss the limit of consequence to which it may be used. After an extensive discussion on the differences between risk, frequency and consequence, accidental situations, failure due to ageing and production faults and other aspects of this very specific containment, which is beyond the current definition of pressure receptacles, some members of the group expressed their wish to not spend too much time on this issue of extremely huge composite containments. A representative of the US DOT explained that in the USA there is a limit of 450 litres for salvage pressure receptacles and there are pressure receptacles approved on the basis of special permits up to 2 Mio bar-litres. He continued that in his view a higher wall thickness didn’t necessarily mean a safer situation. It was stated by several WG-members that pressure receptacles are limited to a water capacity of 3000 litres and have no pressure above 1000 bar (1000 bars are just valid for hydrogen). Most pressure receptacles are made from metal and are far below 1.5 Mio bar litres. The majority expressed again that in their view there is a need for having a pV-limitation.

Nevertheless, there was an interest of EIGA and CGA in staying open for bigger containments, which leads to the idea to consider those very large high pressure containments either as composite tanks or to define a new group of fix mounted containments with a higher volume than pressure receptacles and without a limitation of the pV-product.

The group wished to discuss the task given by the Sub-Committee without any further consideration of containments with a water capacity of more than 3000 litres in its future meetings.

16. Closing comments of the delegates at the end of the 2nd meeting

At the end of the meeting the Chair gave a summary of the situation, which cannot get solved easily because the consideration of a high population density as reference, a low consequence level and a high pV-product are contradictory aspects. He asked each expert for comments on the state of discussion.

In summary, representatives of Belgium, Germany, Sweden, UK, USA, CGA, ECMA, EIGA and ISO, recommended to work for the “red line” and introduce a pV-value to limit worst case consequences for pressure receptacles. All of them are limited to a water capacity of not more than 3000 litres[2]. This lead back to the initial intention of improving the definition and usage of salvage pressure receptacles.

Representatives of China, ECMA, EIGA and ISO stated that further discussions are needed to clarify the use of a reference value for the population density and the value itself.

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[2] Germany proposed in its initial document that exclusively the salvage pressure receptacle should not be limited by water capacity. These should be limited by the maximum pV-product, only.

ECMA and EIGA will discuss some aspects tackled in this meeting with their experts and will provide their official position later.

The Chair asked all participants to check if there are additional arguments that should be considered in the discussion on the pV-product with respect to the sudden failure of a pressure receptacle with a water capacity of not more than 3000 litres. So far, based on the shown analysis a value of 1.5 Mio bar litres seems to be reasonable in the context of criteria like a population density of 6000 pers./km^2 and consequence limits of 30 fatalities or 450 injured persons.

17. WG „pV-Limit" Conclusions for 58th Session of the Sub-Committee

The Chair proposed to finalise the draft of the report within a few days while the group agreed to check the drafted report in the very few days before the 58th Session and to present the outcome as an informal document to the Sub-Committee.

The group is interested in continuing its work and in finding a proposal for a pV-limit. Therefore, the working group asks the Sub-Committee to confirm the continuation of this work.

Appendix 1

BAM

Bundesanstalt für
Materialforschung
und -prüfung

Sicherheit in Technik und Chemie

April 19th, 2021

KICK-OFF MEETING
TDG - INTERSESSIONAL WG on pV-PRODUCT

Impulse Talk

ST/SG/AC.10/C.3/2020/18 of 56th session of TDG Sub-Committee

ST/SG/AC.10/C.3/114 on 57th session of TDG Sub-Committee

BAM

Introduction

Overview

UN-SubCom ETDG – WG „pV-Limit"

Kick-off Meeting

April 19th 2021; 13:00 -17:00 Geneva-Time (CEST)
Contact person: Georg W. Mair; Georg.mair@BAM.de; +49 30 8104 1324

The proposed intention for the first meeting, to which the provisional agenda follows, is to explain in detail the motivation and the steps that led Germany to raise the proposals presented in document "ST/SG/AC.10/ C.3/2020/18" and to discuss the background of the details presented up to now.

Agenda (drafted)

Top 1: **Welcome and opening remarks**

Top 2: **Role of delegates**

Top 3: **Approval of the agenda**

Top 4: **Summary concerning documents and mandate of the UN-SubCom**

Top 5: **General introduction to the concept of limiting the pV-product**

5.1 The basic idea of limiting the consequence to non-catastrophic consequences
(Georg Mair; Impulse talk)
Intention: Avoiding route restrictions by consistently ruling out incidents that would require special disaster response measures.

5.2 Details on the general estimation of consequences caused by a sudden rupture of a pressure receptacle (Presentation Dr. Habib)

Break at about 14:30

Agenda (drafted)

Top 6: **Common discussion of scientific basis for key parameters**

6.1 Determination of a quantity for the maximum acceptable consequence
Intention: Establish a comprehensible limit for the consequence to evaluate the effect of a failure (e.g. number of fatalities).

6.2 Determination of the reference for population density
Intention: Provide the link between physical effect of a rupture and the consequence (e.g. number of fatalities).

6.3 Determination of the critical pressure load on humans
Intention: Provide the link between a pressure wave caused by a rupture and the consequence on humans and buildings.

6.4 Determination of effects resulting from splinters
Intention: Create a joint understanding or the estimation of the effects caused by primary and secondary splinters.

Top 7: **Compilation of the discussion results and their meaning for a pV-limit**

Top 8: **Scheduling of the next meeting**

End at about 17:00

The Task

Report ST/SG/AC.10/C.3/114 says:

Modifications concerning salvage pressure receptacles
Document: ST/SG/AC.10/C.3/2020/18 (Germany)
Informal documents: INF.52 (ECMA) INF.53 (Germany)

35. Following the comments received during the informal session on informal documents INF.52 and INF.53, the Sub-Committee adopted the amendments under proposal 3 in ST/SG/AC.10/C.3/2020/18 (see annex I). It was agreed to set up an intersessional working group led by Germany to further discuss proposals 1 and 2, and to submit a new proposal for consideration during the next biennium.

Role of pV-criteria

Examples for salvage pressure receptacles (SPR)

SPR for pressure receptacles with compressed gases:

There is no limitation of the pressure to which a gas is allowed to be compressed.
With the ongoing increase of pressure levels the former 450 bar-limit for PH is practically not valid any more.

ST/SG/AC.10/C.3/2020/18

taken in the December meeting see ST/SG/AC.10/C.3/114 (Report, page 10)

Proposal 3

11. Since tubes may have a volume of up to 3 000 litres, delete the 1 000 litres limit for pressure receptacles accepted for storage in a salvage pressure (deleted text is ~~struck through~~, new text is underlined):

> "4.1.1.19.2 Pressure receptacles shall be placed in salvage pressure receptacles of suitable size. ~~The maximum size of the placed pressure receptacle is limited to a water capacity of 1 000 litres.~~ More than one pressure receptacle may be placed in the same salvage pressure receptacle only if the contents are known and do not react dangerously with each other (see 4.1.1.6). In this case the total sum of water capacities of the placed pressure receptacles shall not exceed ~~1 000~~ 3 000 litres. Measures shall be taken to prevent movement of the pressure receptacles within the salvage pressure receptacle e.g. by partitioning, securing or cushioning."

ST/SG/AC.10/C.3/2020/18

compare 2014/16 (GER); depending in proposal 3

Since we look for the principle capability to store every pressure receptacle into a SPR we propose to delete the limitation of the water capacity:

Proposal 2

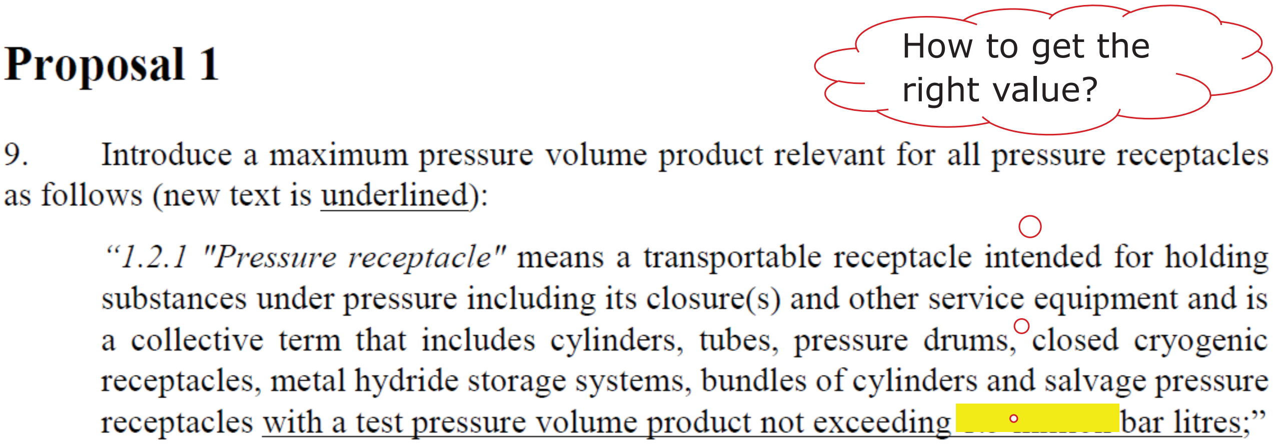
10. Since the pV-limit is valid for all pressure receptacles, delete the volume limit in the definition of salvage pressure receptacles if proposal 1 has been accepted (deleted text is ~~struck through~~):

> "1.2.1 *"Salvage pressure receptacle"* means a pressure receptacle ~~with a water capacity not exceeding 3000 litres~~ into which are placed damaged, defective, leaking or non-conforming pressure receptacle(s) for the purpose of carriage e.g. for recovery or disposal;"

ST/SG/AC.10/C.3/2020/18

Discussion of pV is task of this WG

As alternative measure for limitation of the risk of a SPR we consider the risk that it is not generated by the SPC but by the pressure receptacle stored in:



How to get the right value?

Proposal 1

9. Introduce a maximum pressure volume product relevant for all pressure receptacles as follows (new text is underlined):

> "*1.2.1 "Pressure receptacle"* means a transportable receptacle intended for holding substances under pressure including its closure(s) and other service equipment and is a collective term that includes cylinders, tubes, pressure drums, closed cryogenic receptacles, metal hydride storage systems, bundles of cylinders and salvage pressure receptacles with a test pressure volume product not exceeding [redacted] bar litres;"

Analysis of relevant pV-products

- **SPR for pressure receptacles with pressure liquefied gases:**

  A maximum volume of V 3,000 litres and PH 300 bar leads to a pV of 900,000 bar litres.

- **SPR for pressure receptacles with compressed gases:**

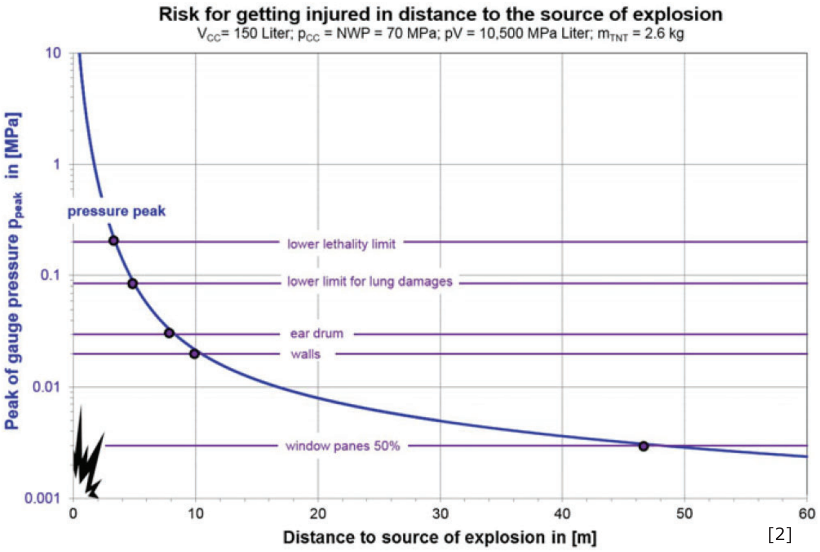
  There is no limitation of the pressure to which a gas is allowed to be compressed. With the ongoing increase of pressure levels the former 450 bar-limit for PH is practically not valid any more (PH 450 bar means a pV of 1,350,000 bar litres).

Are there other arguments for the determination of the maximum pressure?

TOP 6.2 and 6.3

Criteria for estimation of consequences

Pressure waves and critical pressure peaks TOP 6.3



[2]

The damage caused by the pressure wave depends on the distance to the origin.

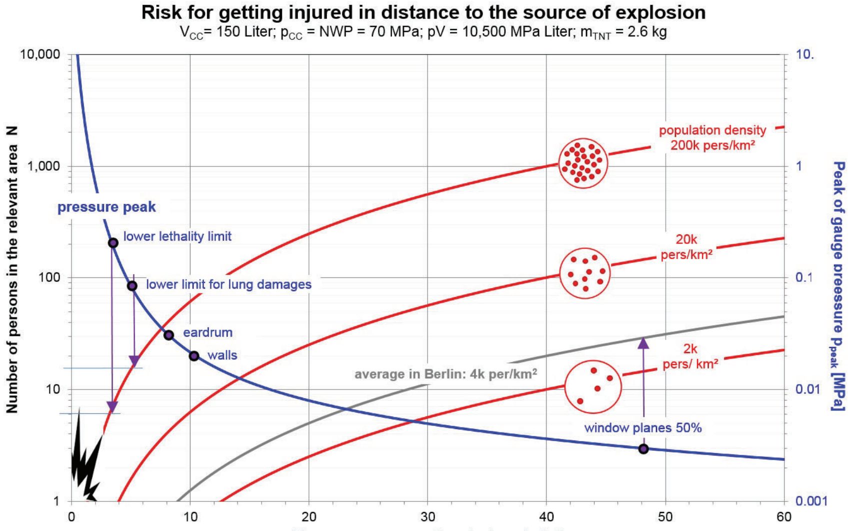
The distance describes a circle around the origin (e.g. rupture of a cylinder) with a related area.

Population density
TOP 6.2

Some numbers for population densities in cities:

- The worldwide highest population density is around 41,000 people/km² in Dhaka.
- The European highest population density is around 21,000 people/km² in Paris.
- Average population density in Berlin is 4000 people/km²
- The North American highest population density is around 22,000 people/km² in Guttenberg.
- The highest population density in Germany is 4686 people/km² in Munich.
- The local density within a city can be much higher.
- Many cities have a lower population density than the largest cities.

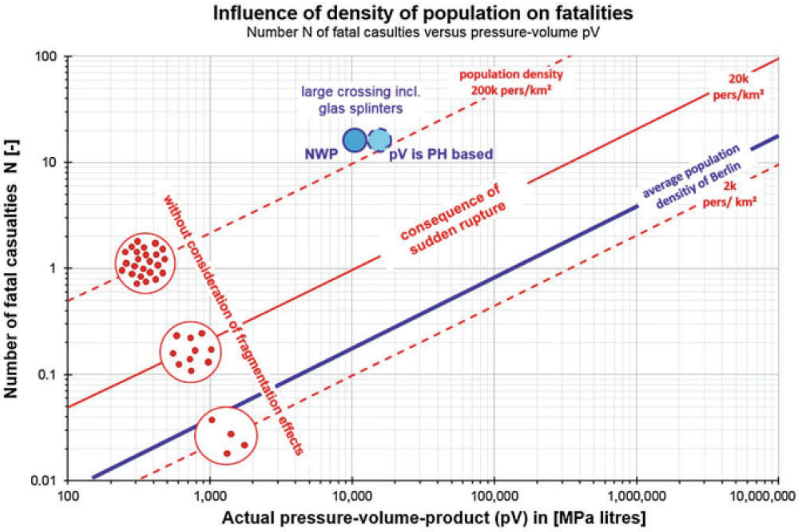
Impact of population density on the number of impacted persons



[2]

Numbers of people injured or killed by pressure wave within the circular area depend on the population density in this area.

Consequence



[2]

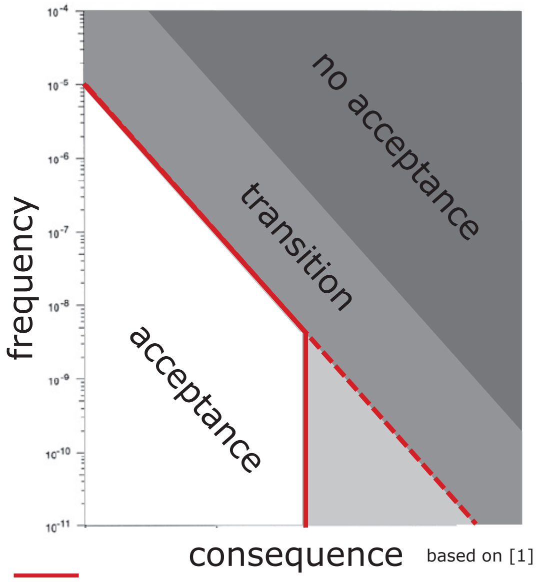
Numbers of injured and killed people correlate with the pressure-volume-product for a given population density (red lines).

The total consequence at a crossing (including splinters: blue dots) is comparable with a pure pressure wave scenario at a density of 200,000 persons/km^2.

TOP 6.1

Criteria for catastrophic consequences

Safety – social risk acceptance



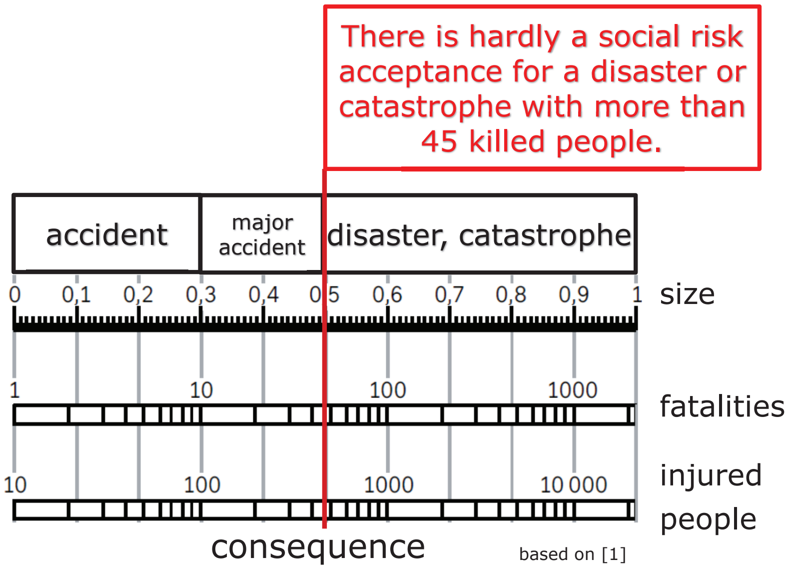
based on [1]

Even below the border line of general acceptance a consequence level equal to a “catastrophe” is not acceptable in transport.

As conclusion it is confirmed that a pressure volume product of 1.5 Mio bar litres based on test pressure – like determined in the EN 17339 – is the appropriate figure for CGH_2.

A more restrictive and gas-specific pV-limitation might be appropriate. But this is not our proposal and should be located in P 200 and not in the definition of pressure receptacles.

Classification of consequences



There is hardly a social risk acceptance for a disaster or catastrophe with more than 45 killed people.

based on [1]

The figure of 45 fatalities is even the border from a major accident to a catastrophe.

Since it is not possible to take measures comparable with stationary facilities we must avoid any catastrophic consequence in principle in the transport of gases in pressure receptacles.

TOP 7

Approach for the limitation of pV-products as a criteria for the avoidance of catastrophic consequences

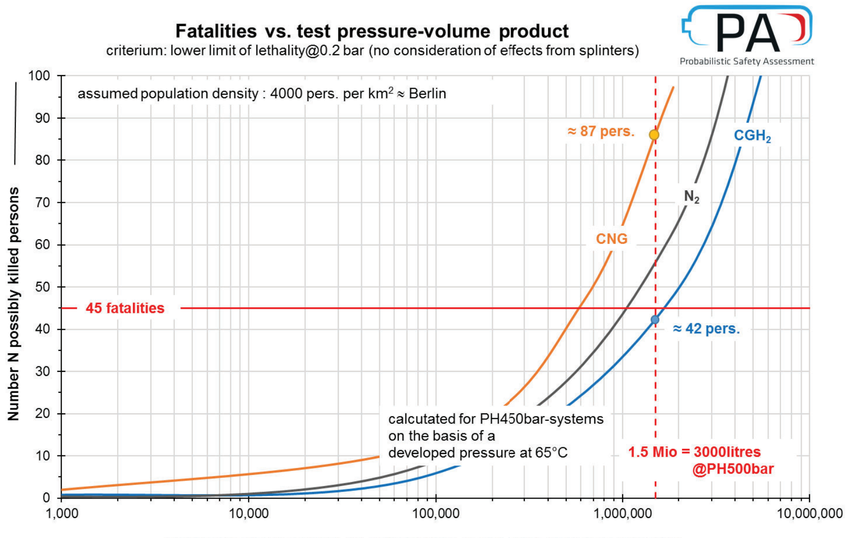
Relevant standardization projects with pV-limits

Standardization projects for composite cylinders and tubes (e.g. EN 17339 and DIS ISO 11515 and ISO TS 17519) address working pressure up to 1000 or 1600 bar.

- In the ISO technical specification ISO TS 17519 a maximum pressure volume of 3 million bar litres on the basis of PW or 4.5 million bar litres on the basis of PH.
- The ongoing ISO-project DIS ISO 11515 discusses the determination of the maximum test pressure volume product between 1.5 and 4.5 million bar litres.
- In EN 17339 for hydrogen purpose only a pressure volume product of 1 million bar litres (PW) or 1.5 million bar litres (PH) is determined.

Is there a rationale for 1.5 Mio bar litres?

Consequence: fatalities as a function of pV-product

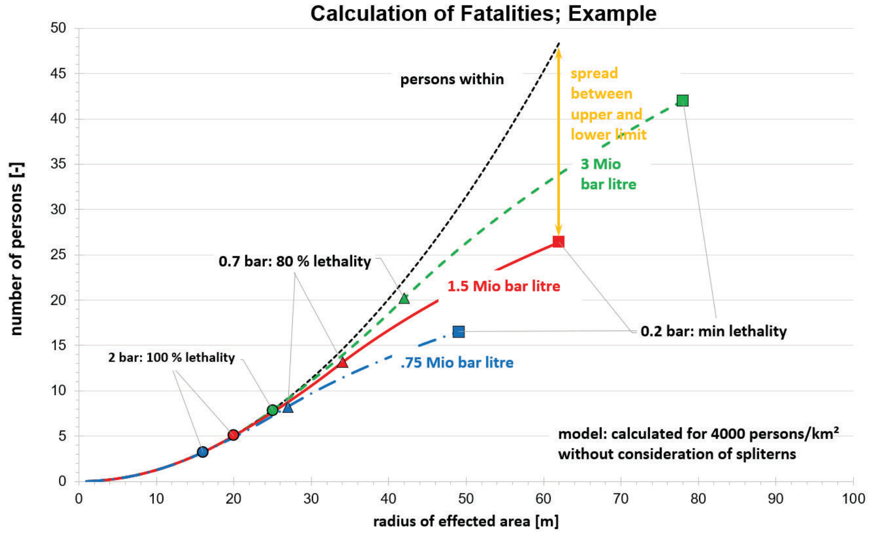


[2]

Pressure waves and numbers of injured and killed people can get estimated on the basis of the pressure-volume-product.

The value of 1.5 Mio bar litres CGH_2 in EN 17339 equals nearly 45 fatalities at a population density of 4000 pers/km^2 (Berlin).

Consequence: fatalities as a function of radius



Pressure waves and numbers of injured and killed people can get estimated on the basis of the radius and the pressure-volume-product.

A critical impact is the determination of the reference population density (here e.g. 4000 pers/km^2 like Berlin).

Conclusion

Summary

- The general limitation of the volume or the pressure is not appropriate for limiting the potential consequences.
- The maximum consequence of a rupture is related to pressure and the water capacity of a pressure receptacle for compressed gases and consequently of a SPR.

We need to agree to reference values for the key issues determining the consequence: ♦ maximum acceptable consequence ♦ reference population density ♦ model for estimating the pressure peak ♦ critical pressure peak value ♦ taking into account splinter effects ♦ how to treat other gases than hydrogen?

Literature

[1] https://www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/handbuch-zur-stoerfallverordnung-stfv-allgemeiner-teil.html

[2] Mair, G.W.: „Safety Assessment of Composite Cylinders for Gas Storage by Statistical Methods“, Springer-Verlag, 2017; ISBN 978-3-319-49708-2

[3] G. W. Mair, S. Thomas, B. Schalau, B. Wang, B.: „Safety criteria for the transport of hydrogen in permanently mounted composite pressure vessels“, international journal of hydrogen energy 46 (2021) 12577-12593.

Thank you for your attention.

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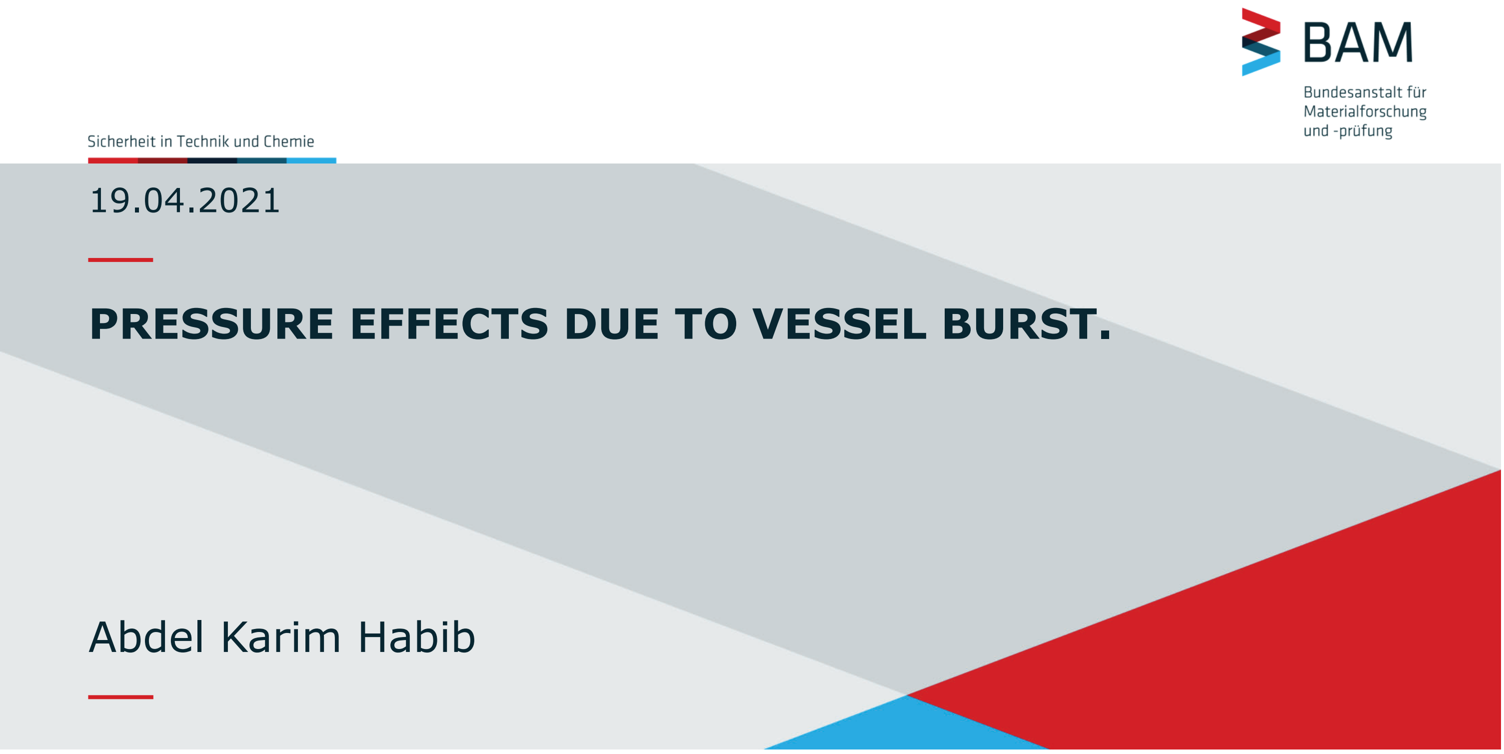
Appendix 2



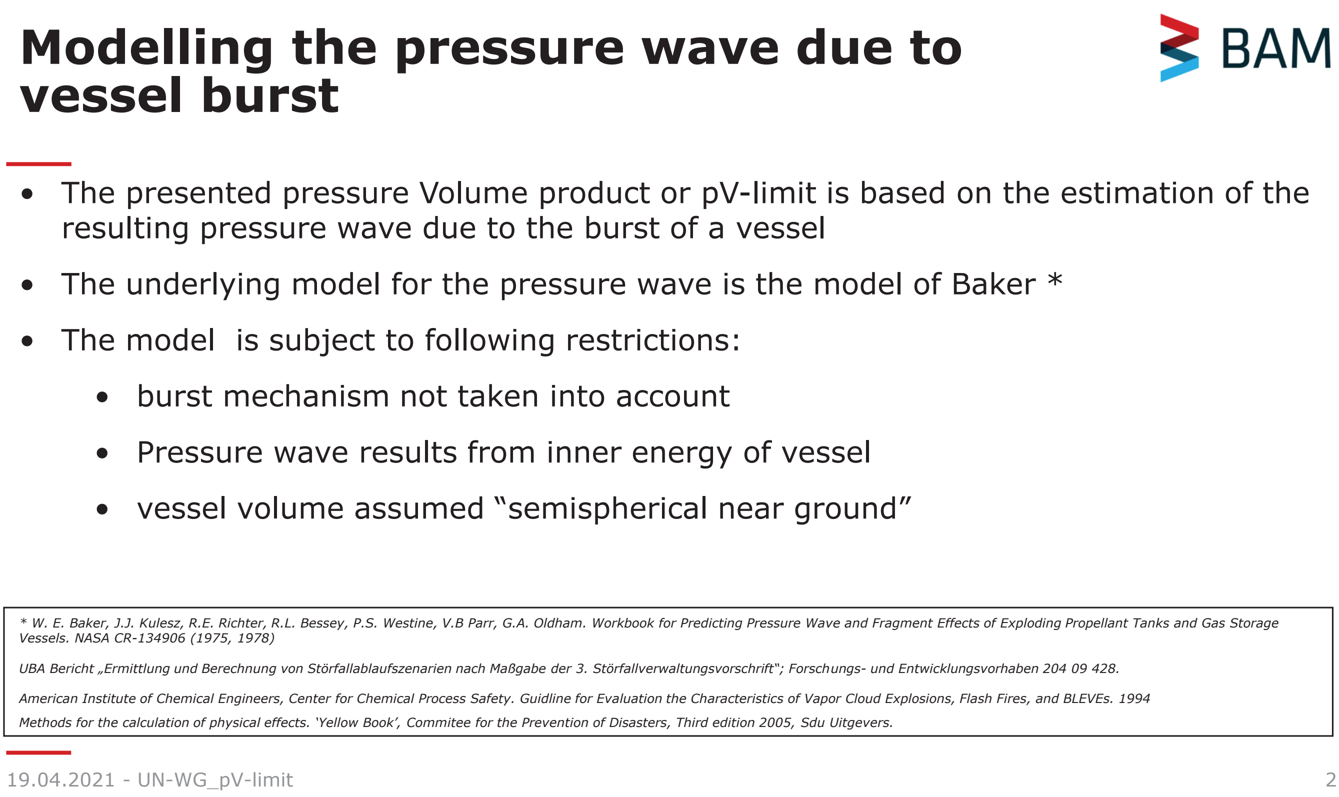
Sicherheit in Technik und Chemie

BAM
Bundesanstalt für
Materialforschung
und -prüfung

19.04.2021

PRESSURE EFFECTS DUE TO VESSEL BURST.

Abdel Karim Habib



Modelling the pressure wave due to vessel burst

- The presented pressure Volume product or pV-limit is based on the estimation of the resulting pressure wave due to the burst of a vessel
- The underlying model for the pressure wave is the model of Baker *
- The model is subject to following restrictions:
    - burst mechanism not taken into account
    - Pressure wave results from inner energy of vessel
    - vessel volume assumed “semispherical near ground”

** W. E. Baker, J.J. Kulesz, R.E. Richter, R.L. Bessey, P.S. Westine, V.B Parr, G.A. Oldham. Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels. NASA CR-134906 (1975, 1978)*

UBA Bericht „Ermittlung und Berechnung von Störfallablaufszenarien nach Maßgabe der 3. Störfallverwaltungsvorschrift“; Forschungs- und Entwicklungsvorhaben 204 09 428.

American Institute of Chemical Engineers, Center for Chemical Process Safety. Guidline for Evaluation the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs. 1994

Methods for the calculation of physical effects. ‘Yellow Book’, Commitee for the Prevention of Disasters, Third edition 2005, Sdu Uitgevers.

Modelling the pressure wave due to vessel burst

For blast effects from vessel bursts "only two methods are more or less generally applicable.

– TNT-equivalence method

– Baker's method.

Both methods are comparable, except that Baker's method distinguishes between close and far range for pressure vessel bursts with ideal gas. For these scenarios Baker's method is more accurate. […] The method can be used for all six types of vessel bursts with a different definition for the available energy for each type of burst."**

- pressure vessel bursts with ideal gas,
- pressure vessel bursts with non-ideal gas or vapour,
- BLEVEs,
- (exothermic) runaway reaction,
- decomposition of energetic materials,
- internal explosion.

*** Methods for the calculation of physical effects. 'Yellow Book', Commitee for the Prevention of Disasters, Third edition 2005, Sdu Uitgevers.*

Modelling the pressure wave due to vessel burst

Basic model equations:

R>2

Liberated or expansion energy:

$$E_{ex} = 2\left(\frac{(P_{Vessel} - P_a)V}{\kappa_G - 1}\right)$$

Non-dimensional distance:

$$\bar{R} = r\left(\frac{p_a}{E_{ex}}\right)^{1/3}$$

R<2

Ratio of speed of sound in the compressed gas to the one in air:

$$\left(\frac{a}{a_a}\right)^2 = \frac{\kappa T M_a}{\kappa_a T_a M}$$

Hemispherical vessel's radius

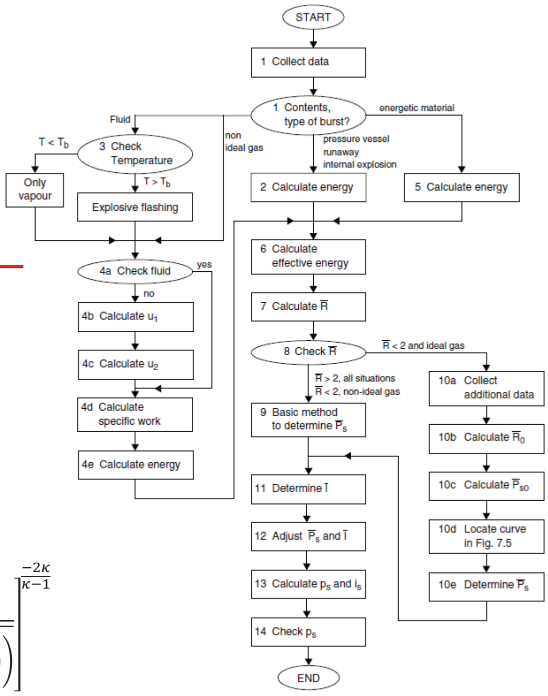
$$r_0 = \left(\frac{3V}{2\pi}\right)^{1/3}$$

Non-dimensional starting distance

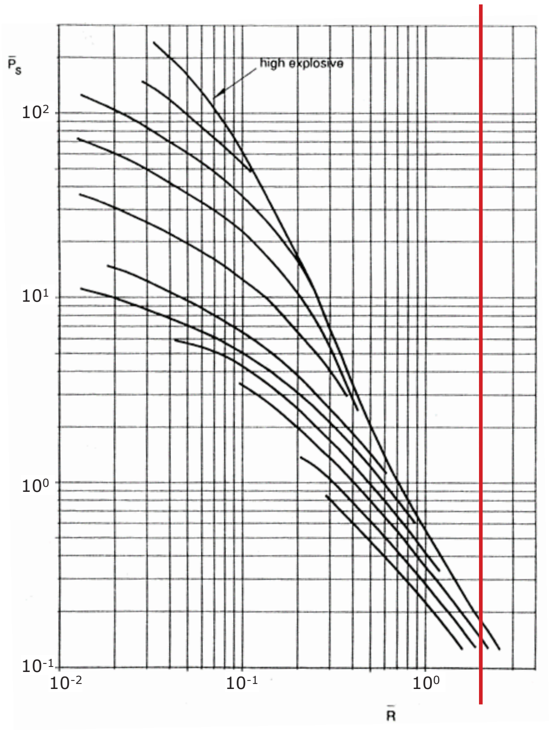
$$\bar{R}_0 = r_0\left(\frac{p_a}{E_{ex}}\right)^{1/3}$$

Initial peak overpressure

$$\frac{p}{p_a} = \left(\frac{p_{s0}}{p_a}\right)\left[1 - \frac{(\kappa - 1)\left({}^{a}/{}_{a_a}\right)\left(\frac{p_{s0}}{p_a} - 1\right)}{\sqrt{2\kappa_a\left(2\kappa_a + (\kappa_a + 1)\left(\frac{p_{s0}}{p_a} - 1\right)\right)}}\right]^{\frac{-2\kappa}{\kappa - 1}}$$



Modelling the pressure wave due to vessel burst



For R<2 :

based on the desired distance r of the „target“, $\bar{R}_0$ is calculated and $\bar{p}_{s0}$ is determined iteratively to find the „correct“ curve for the pressure decay over the distance.

For R>2 :

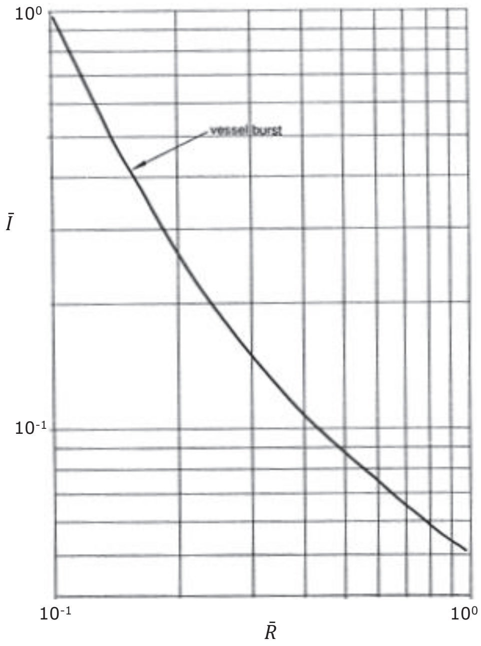
based on the desired distance r of the „target“, $\bar{R}$ is calculated and $\bar{p}_s$ can be read from the diagram on the „high explosive“ line

---

Modelling the pressure wave due to vessel burst

Determination of the non dimensional impulse in analogy to the overpressure

$$I = \frac{\bar{I} p_a^{0,666} E_{ex}^{0,333}}{a}$$



Modelling the pressure wave due to vessel burst

Accounting for geometrical effects:

Vessel is assumed „hemispherical on the ground“ → correction for „real geometry“ necessary.

First investigations showed high overprediction for small cylinders when using correction.

Model uses a modification that blends the corrections factors from 0 to 100 % depending on the vessel Volume.

Table 7.3 Adjustment factors for $\overline{P}_s$ and $\overline{i}$ for cylindrical vessels for various $\overline{R}$ **

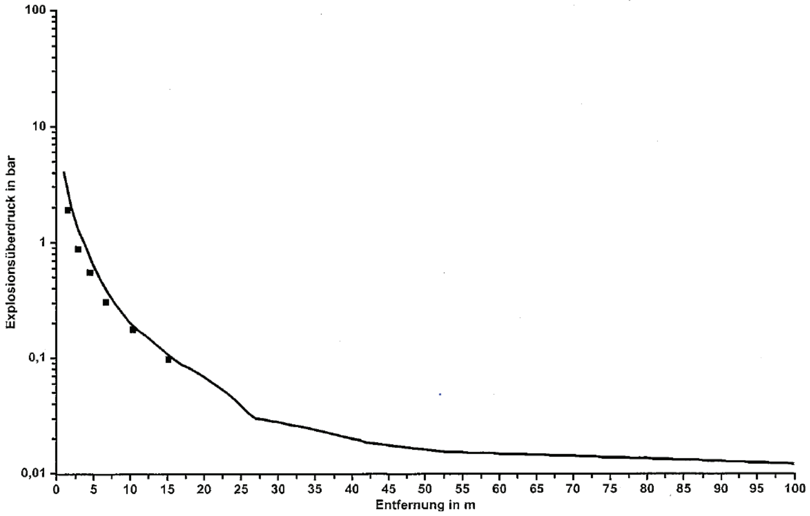
	Multiplier for	
$\overline{R}$	$\overline{P}_s$	$\overline{i}$
< 0.3	4	2
≥ 0.3 and ≤ 1.6	1.6	1.1
>1.6 and ≤ 3.5	1.6	1
>3.5	1.4	1

Table 7.4 Adjustment factors for $\overline{P}_s$ and $\overline{i}$ for vessels slightly elevated above the ground

	Multiplier for	
$\overline{R}$	$\overline{P}_s$	$\overline{i}$
< 1	2	1.6
≥ 1	1.1	1

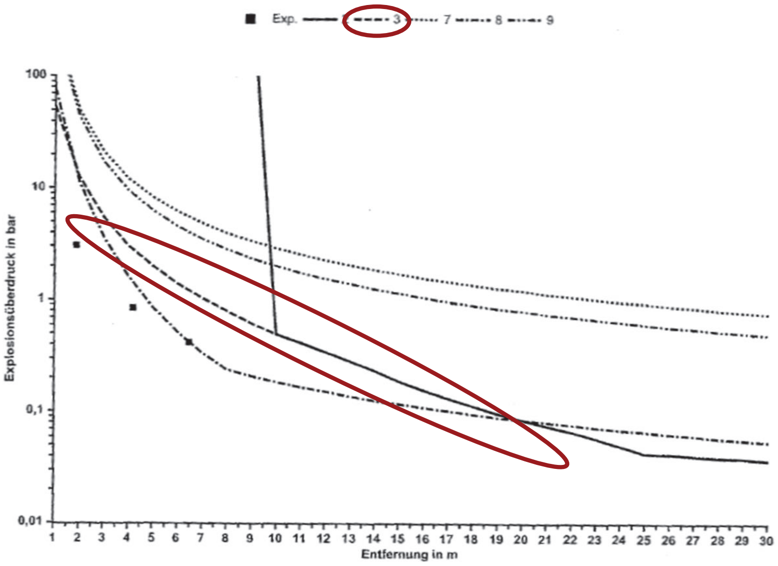
*** Methods for the calculation of physical effects. 'Yellow Book', Commitee for the Prevention of Disasters, Third edition 2005, Sdu Uitgevers.*

Modelling the pressure wave due to vessel burst



1,5 m³
Nitrogen
238 bar

Modelling the pressure wave due to vessel burst



0,0724 m³
Hydrogen
343 bar

Modelling the pressure wave due to vessel burst

Effect	Overpressure [bar]
Loud sound with low frequency	**0,0015**
Very loud bang	**0,003**
Thrwoing over of persons	**0,010**
Pressure threshold for damage due to debris	**0,015**
Lower threshold for rupture of eardrum	**0,175**
Lower threshold for lung rupture	**0,85**
Lower threshold for severe lung damage	**1,85**
Lower lethality threshold	**2,05**

Occasional burst of large windows under tension	**0,002 bar**
Glasburst due to Soundwave	**0,003 bar**
Burst of small windows under tension	**0,005 bar**
Burst of 10% of the windows	**0,01 bar**
Burst of 75% of the windows	**0,03 bar**
Burst of 100% of the windows	**0,05 bar**

**** UBA Bericht „Ermittlung und Berechnung von Störfallablaufszenarien nach Maßgabe der 3. Störfallverwaltungsvorschrift“; Forschungs- und Entwicklungsvorhaben 204 09 428.*

Modelling the pressure wave due to vessel burst

Damage to window frames, doors and walls	0,005
Small damage to roofs	0,020
Brick walls destroyed	0,10
Brick infills of 20 to 30 cm thickness destroyed	0,15
Medium damage on half timbered buildings	0,20
Walls of 24 cm thickness desdtroyed	0,25
Heyva damage to half timbered buildings	0,31
Typical buidlings nearly fully destryoed	0,40
Walls of 50 cm thickness destroyed	0,50

Metal plates damged	0,075
Metal frame of steel frame buildings destroyed	0,095
Burst of oil tanks	0,215
Armed concrete walls deytroyed	0,35
Railroadtanker thrown over	0,46
Loaded railraod tanker thrown over	0,60
Loaded railroad tanke destroyed, 99% damage of horizontal sotrage tanks/chemical reactors and heat exchangers	0,75

**** UBA Bericht „Ermittlung und Berechnung von Störfallablaufszenarien nach Maßgabe der 3. Störfallverwaltungsvorschrift"; Forschungs- und Entwicklungsvorhaben 204 09 428.*

Bundesanstalt für
Materialforschung
und -prüfung

Sicherheit in Technik und Chemie

19.04.2021

THANK YOU FOR YOUR ATTENTION!

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Appendix 3

BAM
Bundesanstalt für
Materialforschung
und -prüfung

Sicherheit in Technik und Chemie

June 17th, 2021

2ND MEETING
TDG - INTERSESSIONAL WG on pV-PRODUCT

Details on Open Issues

BAM

Top 1: Agenda

Overview

UN-SubCom ETDG – WG „pV-Limit"

2nd Meeting

June 17th 2021; 13:00 -17:00 Geneva-Time (CEST)
Contact person: Georg W. Mair; Georg.mair@BAM.de; +49 30 8104 1324

The proposed intention for the second meeting is to tackle the open issues of the last meeting based on the drafted report of the first meeting, the document "ST/SG/AC.10/ C.3/2020/18" and the details presented up to now.

The starting point for the discussion was to limit the pV-product as key criterion for the selection of appropriate salvage pressure receptacles.

Agenda (drafted)

- supported with a presentation

Top 1: **Attendance and short introduction round**

Top 2: **Approval of the report on the last meeting**

Top 3: **Discussion on pressure limits (already distributed table)**

Top 4: **Consideration of injured people and fatalities in the consequence analysis**

Break at about 14:30

Top 5: **Common determination of the reference population density**

Top 6: **WG „pV-Limit" conclusion for 58th Session UN-SubCom ETDG**

Top 7: **Scheduling of the next meeting**

End at about 17:00

Top 2: Summary of last meeting

The task

Report ST/SG/AC.10/C.3/114 says:

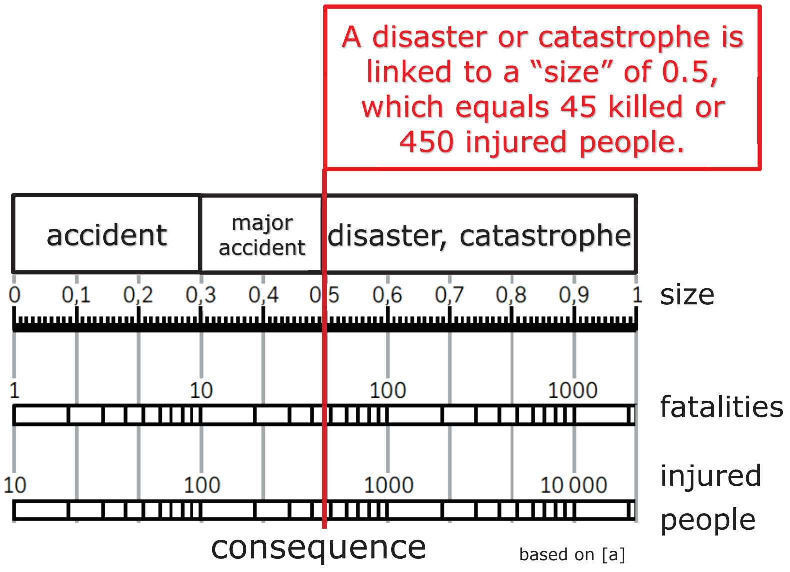
Modifications concerning salvage pressure receptacles
Document: ST/SG/AC.10/C.3/2020/18 (Germany)
Informal documents: INF.52 (ECMA) INF.53 (Germany)

35. Following the comments received during the informal session on informal documents INF.52 and INF.53, the Sub-Committee adopted the amendments under proposal 3 in ST/SG/AC.10/C.3/2020/18 (see annex I). It was agreed to set up an intersessional working group led by Germany to further discuss proposals 1 and 2, and to submit a new proposal for consideration during the next biennium.

Key results of the 1st meeting

1. The limitation of consequences related to pressure receptacles is a common senses, as well as the pV-product as a appropriate criteria for this.
2. The criteria for the determination of a pV-limit is based on several details.
3. There are different models for the calculation of pressure peaks but their variation is not too high in comparison with other uncertainties of the consequence analysis (e.g. splinters).
4. For the consequences caused by a pressure peak the limits given in literature vary, thus a deeper view on details is requested.
5. The populations density of the different member countries varies. Therefore, representatives of member countries has been asked to check their individual values.
6. The limit for the consequence that deems to be acceptable is referenced to a Swiss regulation.

Classification of consequences



A disaster or catastrophe is linked to a "size" of 0.5, which equals 45 killed or 450 injured people.

based on [a]

The value of 0.5 for "size" stands for the threshold from a major accident to a catastrophe.

Since it is not possible to take measures comparable with stationary facilities we must avoid any catastrophic consequence in principle in the transport of gases in pressure receptacles.

Top 3: Pressure limits

Pressure values

(excerpt of the distributed table; incl. references)

Red = value used in analysis

Consequence	Peak overpressure [bar] = [100 kPa]	Ref.
Persons are pushed over (lower level of injuries)	0.01	[2]
Overpressure at limit for debris and missile (splinter) damage	0.02	[2]
50% of windows break	0.03	[2]
First appearance of light injuries due to glass splinters	0.03	[3]
Destruction of brick-walls	0.20*	[4]
Steel frame buildings distorted & pulled away from foundation	0.21	[7]
Serious injuries are common, fatalities may occur	0.21#	[8]
Lower threshold for severe lung damage	1.85*	[2]
Lower lethality limit	2.05 - 2.65*	[2]
50% lethality	2.60	[9]
99% lethality	1.40#-3.50	[9]

"It is the blast wind resulting from the blast overpressure that leads to injuries and fatalities. The human body may be thrown violently into objects and receive blunt force trauma; conversely, large objects may be thrown into persons resulting in crush injuries, or else projectiles launched by the blast wind may penetrate the body. The susceptibility of personnel to blast effects depends on their proximity to nearby objects and possible projectiles." [8]

Pressure values

Proposal for the subsequent analysis

We propose to use the limits - slightly different to the last discussion:

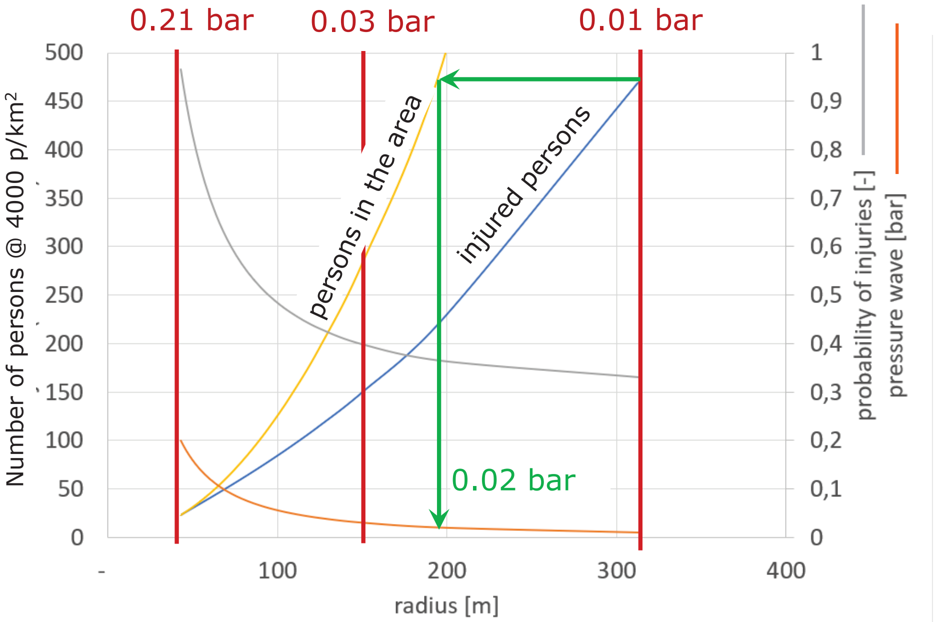
Overpressure at limit for debris and missile (splinter) damage	0.02	[2]
Serious injuries are common, fatalities may occur	0.21#	[8]
99% lethality	1.40#-3.50	[9]

"It is the blast wind resulting from the blast overpressure that leads to injuries and fatalities. The human body may be thrown violently into objects and receive blunt force trauma; conversely, large objects may be thrown into persons resulting in crush injuries, or else projectiles launched by the blast wind may penetrate the body. The susceptibility of personnel to blast effects depends on their proximity to nearby objects and possible projectiles." [8]

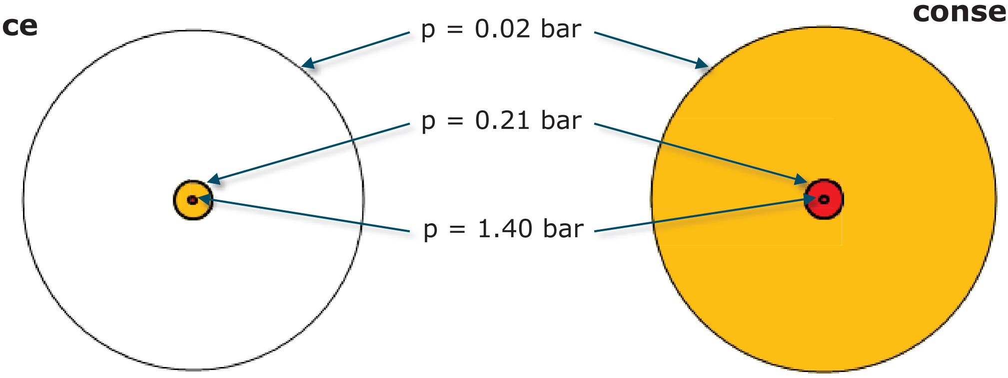
Top 4: Injuries and fatalities

Estimation of consequence
- consideration of injured persons

1. 0.21 bar serious injuries are common
2. 0.03 bar: 50% of windows break
3. 0.01 bar: persons are pushed over and may be injured



Estimation of consequence
(without effects of splinters)



lower value of consequence

upper value of consequence

p = 0.02 bar

p = 0.21 bar

p = 1.40 bar

The truth consequence depends on local aspects and is assumed to be somewhere in-between.

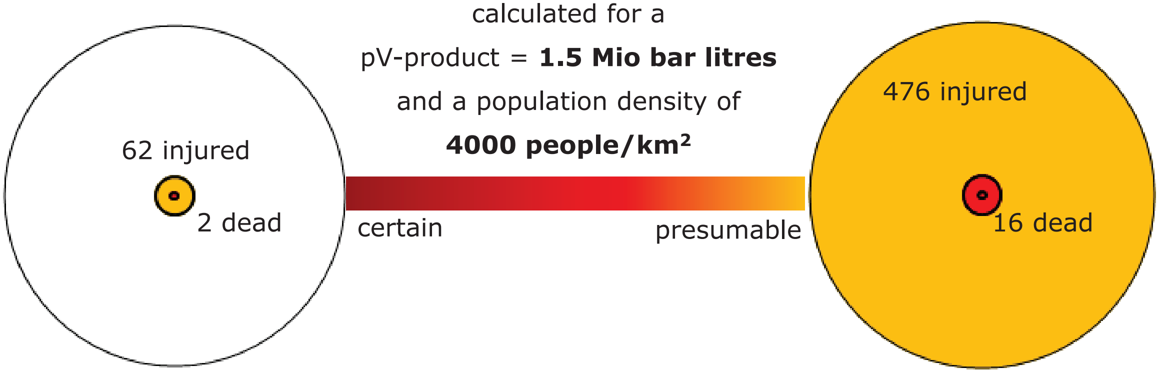
Interpretation of areas: 🔴 100% fatalities 🟡 100% injuries

Exemplary quantification of consequence

(without effects of splinters)

estimation of minimum consequence

estimation of maximum consequence



calculated for a

pV-product = **1.5 Mio bar litres**

and a population density of

4000 people/km²

Interpretation of areas: 🟥 100% fatalities 🟨 100% injuries

Quantification of “consequence size”

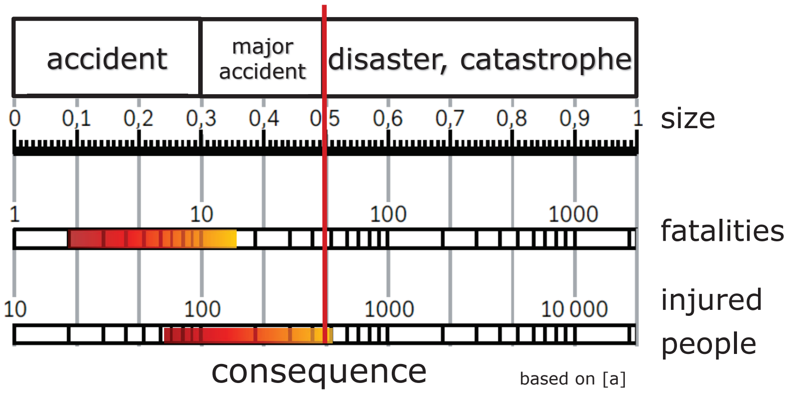
calculated for

pV-product = **1.5 Mio bar litres**

and population density of

4000 people/km²

The number of injured people seems to be the driving criteria!



based on [a]

These figure shows values for the “size”

2 to 16 fatalities

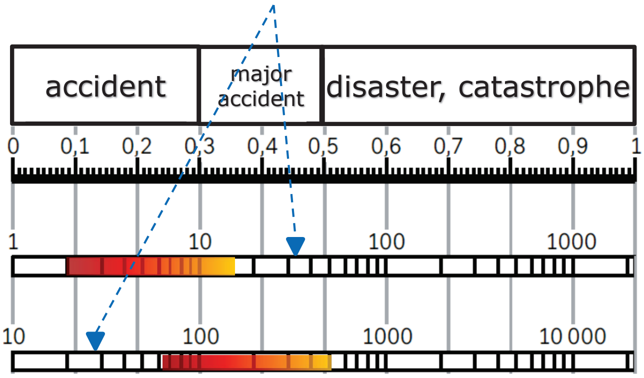
size_{4000} = 0.1 to 0.36

62 to 476 injured people

size_{4000} = 0.25 to 0.51

Viareggio 2009

32 fatalities,
27 injured people

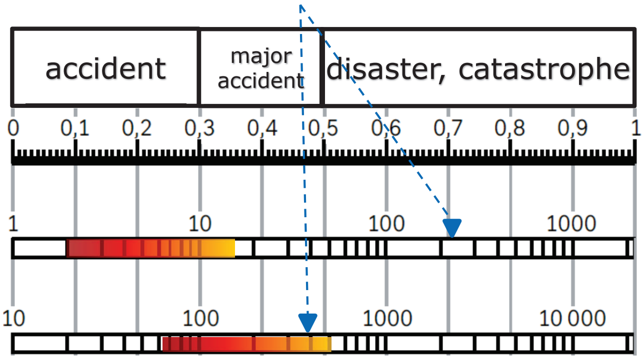


based on [a]

In the Viareggio rail accident, a freight train loaded with liquid butane derailed at the station in Viareggio, Italy, on June 29, and some of its cargo exploded.

Los Alfaques 1978

217 fatalities,
400 injured people



based on [a]

The Los Alfaques tanker accident was a dangerous goods accident in Catalonia, Spain, that occurred on July 11, 1978, on what was then the Carretera Nacional national highway in the area of the Los Alfaques campsite on the Costa Daurada.

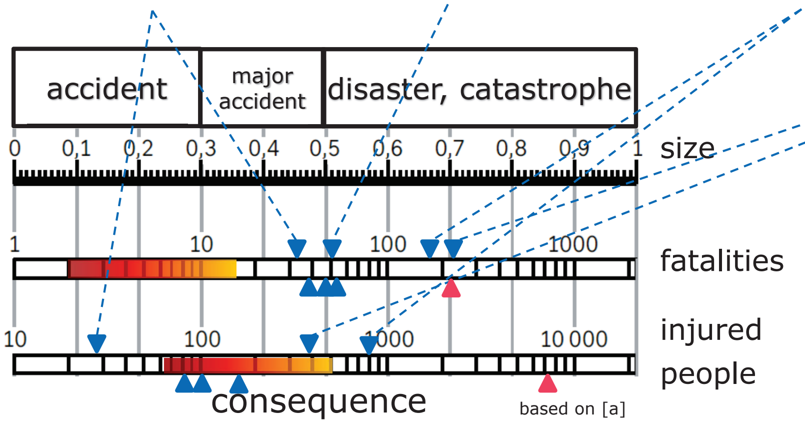
Quantification of “consequence size”

Viareggio 2009
(32 fatalities,
27 injured people)

Lac-Mégantic 2013
(47 fatalities)

Tianjin 2015
(173 fatalities,
797 injured people)

Los Alfaques 1978
(217 fatalities,
400 injured people)



- ▲ Wenling (China) 2020
- ▲ Morogoro (Tansania) 2019
- ▲ Ahumbe (Nigeria) 2019
- ▲ Kongo 2018
- ▲ **Beirut 2020**

https://en.wikipedia.org/wiki/List_of_explosions

Top 5: Population density

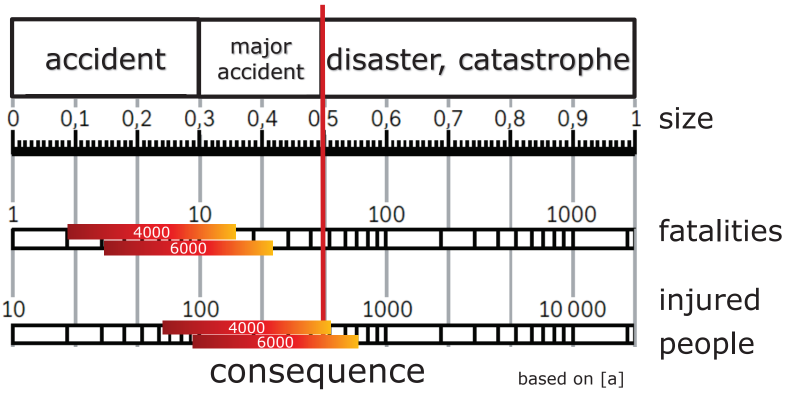
Quantification of “consequence size”

calculated for

pV-product = **1.5 Mio bar litres**

and population density of

4000 people/km² and **6000 people/km²**



There is some space for considering a higher population density.

6000 people/km^2:

3 to 24 fatalities
size$_{6000}$ = 0.15 to 0.42

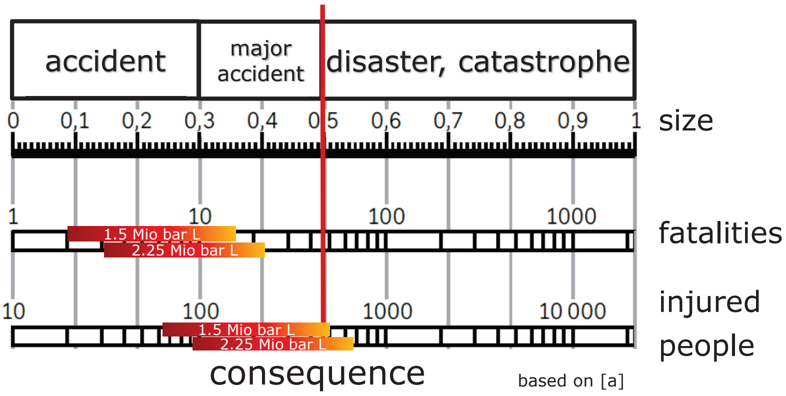
92 to 715 injured people
size$_{6000}$ = 0.36 to 0.56

Top 6: Conclusions

Quantification of “consequence size”

calculated for
pV-product = **1.5 Mio bar litres**
and **2.25 Mio bar litres**
and population density of **4000 people/km²**

Dependent from the population density the pV-product is to be determined.



2.25 Mio bar litres:

3 to 23 fatalities
$\text{size}_{2{,}25\text{Mio barL}} = 0.15$ to 0.41

86 to 659 injured people
$\text{size}_{2{,}25\text{Mio barL}} = 0.34$ to 0.55

Key points to the plenary

- ✓ We started by indicating key issues to which we need to agree to reference values for determining the consequence:
  - ♦ maximum acceptable consequence
  - ♦ reference population density
  - ♦ model for estimating the pressure peak
  - ♦ critical pressure peak value (taking into account splinter effects)
  - ♦ how to treat other gases than hydrogen?
- ✓ We propose to provide an INF-paper as the drafted for the first meeting.
- ✓ This should content the key points and the values as far as we have determined them up to now.

Top 7: Schedule of the next meeting

Thank you for your contribution

Contact:

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Literature

[a]
https://www.bafu.admin.ch/bafu/de/home/themen/stoerfallvorsorge/publikationen-studien/publikationen/handbuch-zur-stoerfallverordnung-stfv-allgemeiner-teil.html

Mair, G.W.: „Safety Assessment of Composite Cylinders for Gas Storage by Statistical Methods“, Springer-Verlag, 2017; ISBN 978-3-319-49708-2

G. W. Mair, S. Thomas, B. Schalau, B. Wang, B.: „Safety criteria for the transport of hydrogen in permanently mounted composite pressure vessels“, international journal of hydrogen energy 46 (2021) 12577-12593.

Appendix 4

May 2021

Overpressure values used for the calculation of consequences

Consequence	Peak overpressure [bar] = [100 kPa]	Ref.
Minimum damage to glass panels	0.002	[5]
Persons are pushed over (lower level of injuries)	0.01 0.07 - 0.10 0.14 – 0.20	[2] [5] [1]
Damage to window frames, doors and roofs	0.01	[1]
10% of windows break	0.01	[2]
Overpressure at limit for debris and missile (splinter) damage	0.02	[2]
50% of windows break	0.03	[2]
First appearance of light injuries due to glass splinters	0.03	[3]
75% of windows break	0.05	[2]
Partial demolition of houses; made uninhabitable	0.07	[7]
100% of windows break	0.10	[2]
Light to medium damage to living quarters	0.12	[3]
Partial collapse of walls and roofs of houses	0.14	[7]
People injured by flying glass and debris	0.14#	[8]
1% probability of eardrum rupture	0.17 0.34 0.35	[7] [6] [9]
Destruction of brick-walls	0.20*	[4]
Steel frame buildings distorted & pulled away from foundation	0.21	[7]
Serious injuries are common, fatalities may occur	0.21#	[8]
Near total destruction of remaining buildings	0.40	[2]
50% probability of eardrum rupture	0.44 1.00	[7] [9]
Lower threshold for lung damage	0.70 0.85* 0.83	[9] [2] [6]
90% probability of eardrum rupture	0.84	[7]
Lower threshold for severe lung damage	1.85* 1.72	[2] [6]
Lower lethality limit	1.00 1.80 2.05 - 2.65* 2.76	[7] [9] [2] [6]
50% lethality	2.60 2.65 - 3.45* 4.27	[9] [4] [6]
99% lethality	1.40# 2.00 3.30 - 4.50* 3.50 6.34	[8] [7] [4] [9] [6]

* Numbers from [2] that originated from [4] are reported in [2] at half their reported magnitude according to the following reasoning translated from [2]: "*During the compilation of this report the perpendicularly reflected blast pressures were used. Deviating from that, values with half this magnitude are used here [in this table], which suitably represent the peak overpressure of an uninhibited pressure blast wave."* This reasoning was also applied to numbers cited directly from [4].

\# "It is the blast wind resulting from the blast overpressure that leads to injuries and fatalities. The human body may be thrown violently into objects and receive blunt force trauma; conversely, large objects may be thrown into persons resulting in crush injuries, or else projectiles launched by the blast wind may penetrate the body. The susceptibility of personnel to blast effects depends on their proximity to nearby objects and possible projectiles." – excerpt from [8]

References

[1] Mustersicherheitsanalyse nach §7 Störfallverwaltungsvorschrift für eine Sprengstofffabrik, Forschungsbericht 104 09 211, UBA-FB 92-026, Band 1, BAM im Auftrag des Umweltbundesamtes, 1991, pp. 84-91 (Paradigm safety analysis, BAM on behalf of the Federal Environment Agency of Germany)

[2] UBA Bericht „Ermittlung und Berechnung von Störfallablaufszenarien nach Maßgabe der 3. Störfall-verwaltungsvorschrift“; Forschungs- und Entwicklungsvorhaben 297 48 428, Band 2, BAM im Auftrag des Umweltbundesamtes, 2000, p. 194 (Report on investigation and computation of incident scenarios, BAM on behalf of the Federal Environment Agency of Germany)

[3] Richtlinie des Bundesministers des Innern (RSI-513 145/1), 376 (Directive of the Federal Ministry of the Interior of Germany)

[4] The scope of blast and shock biology and problem areas in relating physical and biological parameters, Ann. New York Acad. Sci., 1968, p. 89 (10 ms overpressure duration)

[5] Explosive Shocks in Air, Springer Berlin Heidelberg, 1985, p. 260

[6] The Effects of Nuclear Weapons, United States Department of Defense and United States Department of Energy, 1977, p. 552 (fast-rising, long-duration pressure pulse)

[7] Loss Prevention in the Process Industries, Vol. 1, London and Boston: Butterworths, 1980, p. 17/238

[8] Zipf and Cashdollar, Effects of blast pressure on structures and the human body, CDC Report

[9] Fire Dynamics Tools (FDTs): Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program, NUREG-1805, U.S. Nuclear Regulatory Commission, Washington DC, 2004

Appendix 5

Robustness of T4 large tubes relative to design parameters

This document is a draft preparation for relevant ISO WGs, but also relevant for the ongoing discussions at UN-SCETDG intersessional Working Group regarding limitation of energy content in large tubes

Per S. Heggem
Rev 1 - 17.06.2021

Large tubes (>3000L) in Service

- More than 3800 tubes
- 3 independent manufacturers
- Service in 14 countries
- More than 10 years experience

- Several incidents demonstrating robustness.
- No loss of life.

Field experience tubes larger than 2M barL

Tube trailer overturned during transportation.

- Tube 1.07m x 11.6m, 250 bar, 8500L, pXV 2.125.000 barL.
- Energy 520 MJ, TNT equivalent 155 kg.
- Tube dome penetrated by steel post, approximately 200mm hole.
- Tube vented, did not rupture, defect did not propagate.
- Driver was not seriously affected by escaping gas pressure.

Tube trailer hit by 40mm shoulder fired grenades

- Tube 1.07m x 11.6m, 250 bar, 8500L, pXV 2.125.000 barL.
- Energy 520 MJ, TNT equivalent 155 kg.
- no leak or rupture.

Reference and calculated values for larger tubes

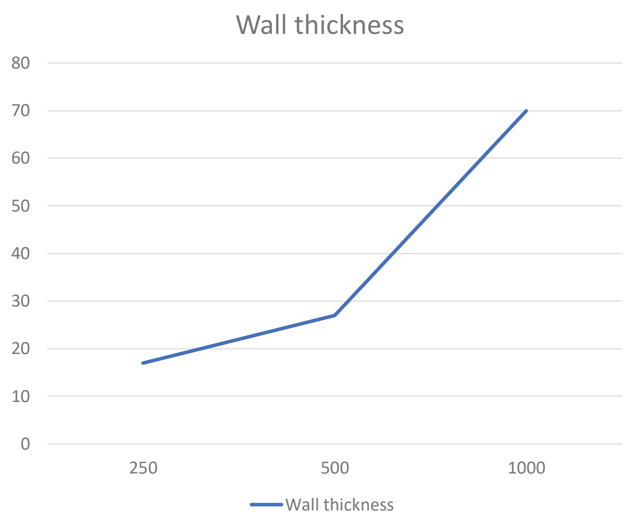
- Reference tube volume (V): 2000 L
- Reference tube length (L): 12.000 mm
- Variables:
  - Tube diameter: 500->1000 mm
  - Pressure: 250 –> 1000 bar
- Calculated values:
  - Structural wall thickness: t mm
  - Energy content: pxV barL

pxV discussion

- The discussion so far focus on blast wave and number of people injured.
- Maximum length of large tubes that can be transported on road is limited to the maximum length of the trailer that can be used on roads. Increased volume will be by increased tube diameter.
- Increased amount of energy transported will be by either increased volume and/or increased pressure, which both will increase the wall thickness of the structural composite exponentially due to the thick wall effect in the structural composite.
    - Consequence of external impact on the outermost layers has less effect than on thinner wall structural composite.
    - Thicker wall structural composite will lose performance in fire slower than thinner structural wall thickness.

Structural wall thickness as function of p

V	d	p	t	pxV
2000	500	250	17	500.000
2000	500	500	27	1.000.000
2000	500	1000	70	2.000.000

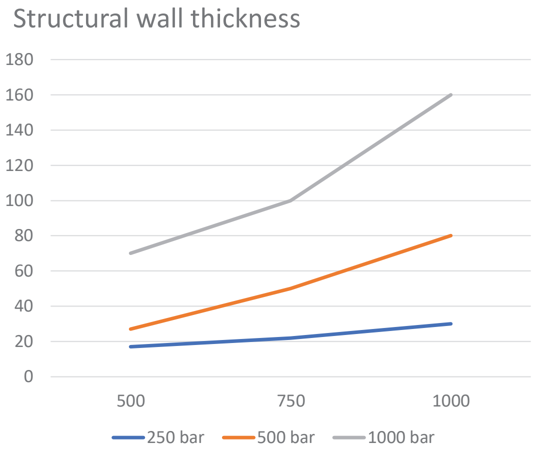


Structural wall thickness as function of d and p

Pressure	d	V	t	pxV
250	500	2000	17	500.000
250	750	5000	22	1.250.000
250	1000	8600	30	2.150.000

500	500	2000	27	1.000.000
500	750	5000	50	2.500.000
500	1000	8600	80	4.300.000

1000	500	2000	70	2.000.000
1000	750	5000	100	5.000.000
1000	1000	8600	160	8.600.000



Conclusion and recommendation

- Increased energy content represented by pxV will reduce the risk a catastrophic incident significantly.
- As the length of any transportable unit will be limited by the maximum trailer length on the roads, increased pxV can only be achieved by increasing p or d of large tubes, which automatically generate a significant increase in robustness of the large tubes.
- Volume and weight that can be transported will automatically be limited by the maximum dimensions and load capacity a transport module can carry.
- The threat in form of external impact and fire remains constant and independent of the pxV content but the related risk is significantly reduced.
- The risk for a catastrophic incident is significantly reduced with increased energy content compared to what is possible with the 3000L limitation in the UNMR/ADR today.