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Safety criteria for the transport of hydrogen in permanently mounted composite pressure vessels

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HIGHLIGHTS

- New safety approaches require independent evaluation: quantitative risk assessment.
- Failure rate vs. pressure-volume product can be used for risk acceptance criteria.
- A pV-product of 1 Mio bar-litres has the potential for catastrophic consequences.
- The probabilistic assessment of elements enables to control of risk of vehicles.
- The batch test results from mass production should be used as data base.

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ABSTRACT

The recent growth of the net of hydrogen fuelling stations increases the demands to transport compressed hydrogen on road by battery vehicles or tube-trailers, both in composite pressure vessels. As a transport regulation, the ADR is applicable in Europe and adjoined regions, and is used for national transport in the EU. This regulation provides requirements based on the behaviour of each individual pressure vessel, regardless of the pressure of the transported hydrogen and relevant consequences resulting from generally possible worst case scenarios such as sudden rupture. In 2012, the BAM (German Federal Institute for Materials Research and Testing) introduced consequence-dependent requirements and established them in national transport requirements concerning the “UN service life checks” etc. to consider the transported volume and pressure of gases. This results in a requirement that becomes more restrictive as the product of pressure and volume increases. In the studies presented here, the safety measures for hydrogen road transport are identified and reviewed through a number of safety measures from countries including Japan, the USA and China. Subsequently, the failure consequences of using trailer vehicles, the related risk and the chance are evaluated. A benefit-related risk criterion is suggested to add to regulations and to be defined as a safety goal in standards for hydrogen transport vehicles and for mounted pressure vessels. Finally, an idea is given for generating probabilistic safety data and for highly efficient evaluation without a significant increase of effort.

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List of abbreviations

ALARP	As low as reasonably possible
AR	Acceptance rate
BP	Burst pressure
BP _o	Midpoint burst pressure (GTR No. 13)
C	Consequenced
d	distance
cp.	Ceteris paribus
CPV	Composite pressure vessel
F	Frequency
FR	Failure rate
HTV	Hydrogen transport vehicle
m	mass of gas
MSP	Maximum service pressure
n	number of events
N	Number of fatalities
NWP	Nominal working pressure (vehicle regulations)
p	Pressure
PH	Test pressure (transport of dangerous goods)
PW	Working pressure (transport of dangerous goods)
RR	Rejection rte
RTP	Risk-specific transport performance
TRV	Transport-specific risk value
V	Volume; i.e. water capacity of an PV

Introduction

In the second decade of the 21st century, we currently experience an early stage of hydrogen fuel cell vehicles (HFCV) use, which is combined with road transport for the delivery of compressed gaseous hydrogen (CGH₂). This means of gas transport is an attractive and economical option due to the still widely-meshed net of filling stations and the relatively low capacity of installed infrastructure, [1]. The increase in the amount of transported hydrogen on the road and the developments of new designs and materials require the current regulations, codes and standards (RCS) to be improved quickly in response. A vehicle for the transport of hydrogen using composite pressure vessels (CPVs) is shown in Fig. 1. To evaluate new developments or new technologies, extensive knowledge and experience from the operation of storage systems are needed.

Based on the experience, the appropriate test procedures and acceptance criteria can be defined [2,3]. In Japan, New Energy and Industrial Technology Development (NEDO) conducted a research project called “Regulation Reviews concerning Construction and Operation of Hydrogen Stations” [4]. During this research project, Kawasaki Heavy Industries developed two designs for hydrogen trailers equipped with 35 or 45 MPa composite pressure vessels (CPV). They introduced the preconditions for the operation and handling of the hydrogen transport vehicle (HTV), e.g. a qualified driver, pre-determined routes and frequent inspections for leakage and over pressure. In addition, they developed a design concept to improve the safety measures including vibration and collision



Fig. 1 – State of the art vehicle for the transport of hydrogen in central Europe, based on CPVs (Co. Linde).

tests to prevent leakage of the pressure vessels, valves and piping.

Safety measurements for the two mobile hydrogen filling stations operating during the Expo 2010 in China provided another example for dealing with equipment for hydrogen, including transport vehicles. K. Sun et al. (2014) [5] performed the risk and consequence assessments using process hazard analysis. They conducted a quantitative risk analysis (QRA) case study on mobile hydrogen filling stations in operation during the World Expo, including the safety for transport vehicles. F-N curves are used to determine the acceptable probability of failure according to acceptable risk values. The risk acceptance criterion of 10^{-6} per year for CPV is based on the results of the European Integrated Hydrogen Project (EIHP2) from 2003, [6]. The risk acceptance criteria for hydrogen refuelling stations are also referenced to EIHP2 project.

In addition to the risk analyses carried out in [5], an efficiency study of using composite tube trailers to transport hydrogen gas was done in the USA, [7]. A model was developed to calculate the efficiency in the aspects of payloads and costs under USA weight and size constraints. The study evaluated the impacts of various transport vehicle configurations and payloads on the transportation and refuelling cost of hydrogen under various transportation distance and capacity scenarios for hydrogen filling stations. It concludes that a configuration of HTVs with smaller pressure vessels packed in larger numbers holds higher payloads compared to configurations with smaller numbers of large pressure vessels. Together, the three examples from Japan, China and the USA show the safety measures and economics factors associated with using tube trailers to transport hydrogen. They provide the valuable experiences of dealing with safety issues regarding hydrogen transportation.

In the following paper it is explained why it is necessary to introduce a new approach for the assessment of pressure vessels, which considers and describes the safety goal of regulations and codes or standards referenced in regulations. A risk-based definition of safety is suggested, which is derived from the consequence and the probability of worst-case scenarios. By taking pressure wave simulations and experiments into account, the maximum acceptable failure probability as a

function of the pressure-volume product is derived. In the transport sector, the design of a vehicle has a considerable influence on the inherent risk. To explore the limits of the probabilistic approach, it is compared to an approach comparing the risk and the economic benefit to determine the accepted risk values. For this, an example comparison of two different transport vehicles for hydrogen is provided. Lastly, recent changes to regulations for type approval of pressure vessels for the hydrogen propelled vehicles are investigated with the probabilistic approach. For generation of necessary data without additional effort, suggestions are made concerning production control of pressure vessels based upon burst strength results from batch testing.

Purpose of regulations for vehicles and transport

To achieve safety in hydrogen transport, legally binding criteria for the approval and usage of transport vehicles are needed. Therefore, according to e.g. the German law for the transport of dangerous goods (GGBefG [8]), the use of containments for the transport of a dangerous good is generally forbidden unless an approval is granted in accordance with relevant regulations, technical codes and standards (RCS).

Determination of the legal basis is the sovereign task of a state or a community of states. International conventions and EU directives become legally binding in individual EU member countries by national laws and ordinances/statutory instruments. Nevertheless, those national rules and laws usually refer to the internationally harmonised regulations, which provide all the technical details like the testing procedures.

To provide every citizen a strong legal basis for his or her rights and obligations, rules must be robust for a certain period. In contrast, science and technology develop continuously but at varying speeds. For example, the bronze dagger was once a revolutionary idea, but those ideas are now either common property or no longer in use.

Regarding the level of technical development, a distinction is made today between three levels: “state-of-the-art technology” (SoAT), “state of safety engineering” (SoSE) and “state of science and technology” (SoST) (cf [9]). SoAT expresses the general level of knowledge in which an approval issued once is fixed and does not need subsequent or additional measures in the future. If SoSE is required, additional safety measures are requested. This involves a regularly conducted search for the newest safety technologies with the consequence of upgrading safety equipment of running systems. SoST requires the highest level of precautions with potentially high effort for keeping a system at the level of science and technology. Those high requirements are not relevant for mobile systems for which an upgrade in service is economically unviable. As shown in Fig. 2, what once corresponded to the SoST will later correspond to the SoAT.

On the other hand, RCS do not automatically represent a certain level of technology. RCS are just the “rules of technology” whose determination is reserved for the rule-setter or regulator, aimed at ensuring citizens’ right to health with a reasonable effort. Regulators follow the basic rules of comparativeness to manage appropriate measures.

Regulations for the transport of dangerous goods are periodically revised at 2-year intervals and are usually adjusted to the SoAT. In cases of new technologies or severe consequences, a measure based on the current level of SoSE or SoST is considered and therefor evaluated regarding the effectiveness and cost of the measure. The implementation of new rules for the different modes of transport takes place with a time lag of about 4 years from recognition of the need for change. The “general rules of technology” below are based on the state of the art of the long-term level of training, and are explicitly excluded from approval (e.g. [11]).

What is approved in Europe according to such a regulation is considered safe. Thus, this regulation with the acceptance criteria for approval determines the resulting level of safety. These approval requirements may strongly differ in their approach and their understanding of the term “safety,”

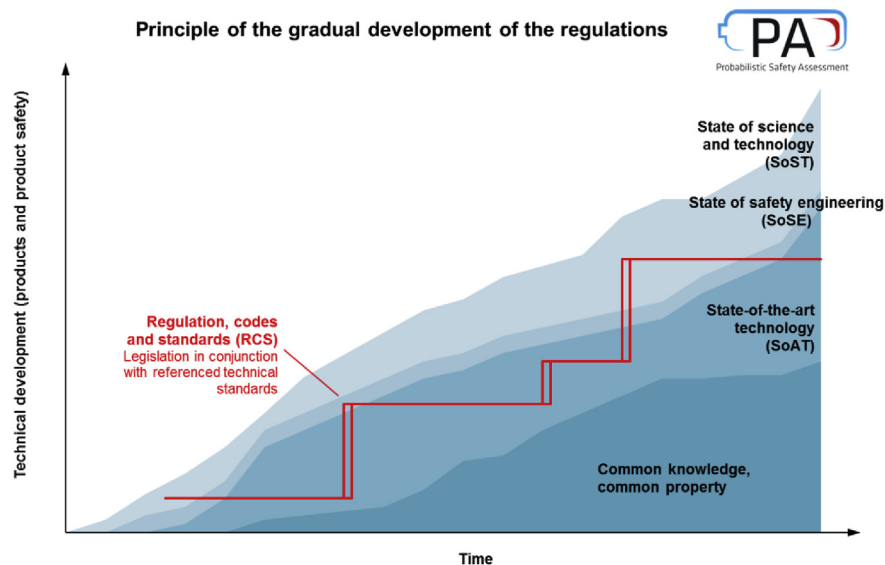


Fig. 2 – Continuous development of the technology and the step-by-step updating of the law, cp. [10].

depending on the contained gas, the gas pressure and the use case. Therefore, the following section provides an attempt to explore the meaning of the term “safety” for gas storage and an approach for a general definition of safety, which can be used across a broad spectrum of rules, codes and standards for pressure vessels.

Based on these established processes of well-organised committees and panels, there is an increasingly critical effect resulting from the rate of technology development. The cycles of development are becoming shorter while the resulting steps of developing experience and loops for adequate regulations are increasing. This leads to a situation in which the work to improve RCS for existing technologies has become more complex, while adequate regulations for new technologies are more and more behind the market and public needs.

The way out could be a hereby presented, more general understanding of safety, and a switch from rules focusing on technical measures to rules providing general approaches for the demonstration of safety in a global sense, i.e. independent from SoAT/SoSE or SoST and preferably with a probabilistic focus.

This would finally mean that regulations determine the level of risk that is deemed acceptable for a technology. Then in terms of work-sharing, codes and standards describe how the demonstration of guaranteed survival rate and maximum consequence shall be performed.

The definition of safety

To evaluate new developments or new technologies, a minimum of experience with this technology is needed. This enables the determination of appropriate test procedures and acceptance criteria. These acceptance criteria traditionally refer to the minimum wall thickness and a hydraulic pressure proof test, [12]. With respect to pressure vessels made from composites, a more “performance based” test approach was established. There the burst test, load cycle test, extreme

temperature load cycle test, drop test, high velocity impact test, accelerated stress rupture test, etc. are requested (e.g. [13]).

However, technological development is progressing at an ever-increasing pace. This means that the time span in which this necessary experience can be gathered is getting shorter and shorter. Simultaneously, the time span in which the standardization projects should be completed is also becoming shorter, hence, the number of corrections to finished standards is increasing.

This reduces the resilience of conventionally developed safety requirements and increases the need for alternative approaches to safety assessment. The principle of such an approach was proposed by Mair in 2005, [14]. It is a risk-based interpretation of safety, which will be explained in more detail here.

The authors define risk as the combination of probability/frequency and consequence of an event, which are both quantifiable. Safety is a situation that is achieved when the actual risk during the use of a technology is below the acceptable risk level. Otherwise a state of danger is present. A situation or the condition of a pressure vessel is either safe or dangerous; there is nothing in-between. The limits of the acceptable risk are usually described in the so-called F-N-diagrams (frequency-number of fatalities-diagram). These diagrams show an accepted level of the failure rate F per year and plant. F decreases with the increase of consequence in terms of number of fatalities N or property damage. One set of values of F-N diagrams widely accepted in Europe is presented in Fig. 3 as anchor points. These points are based on an F-N-diagram deduced from the one of Switzerland [15], with additional aspects from the one of the Netherlands, indicated by CH and NL respectively.

Also, the concept ALARP (as low as reasonably practicable) is used. From this, the anchor point for the acceptable area border is chosen to be 10^{-5} per year for one casualty with an aversion factor of -2 . The aversion factor -2 means that for an increase in the number of deaths by a factor of X , the probability must be decreased by a factor of X^2 . The not acceptable

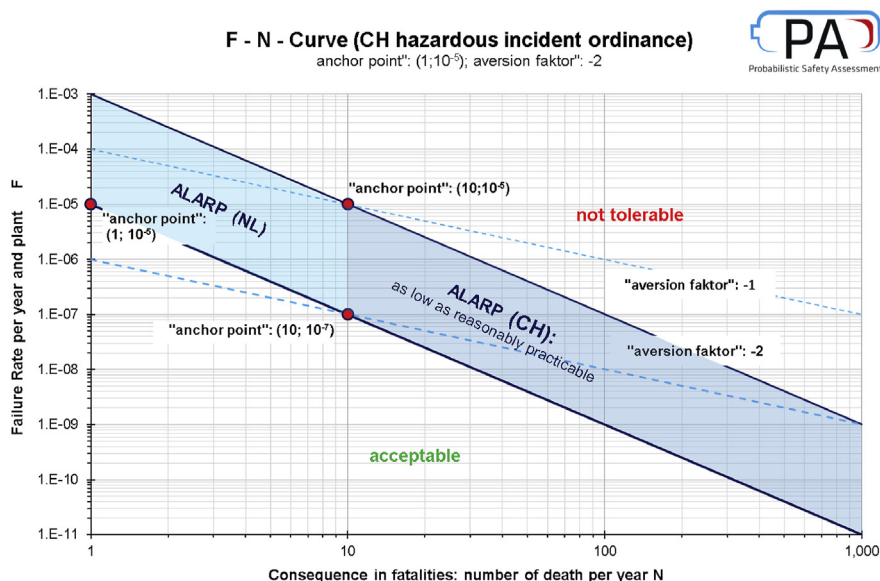


Fig. 3 – F-N-curve as used in Europe (cp. Fig 5.2 in [18]).

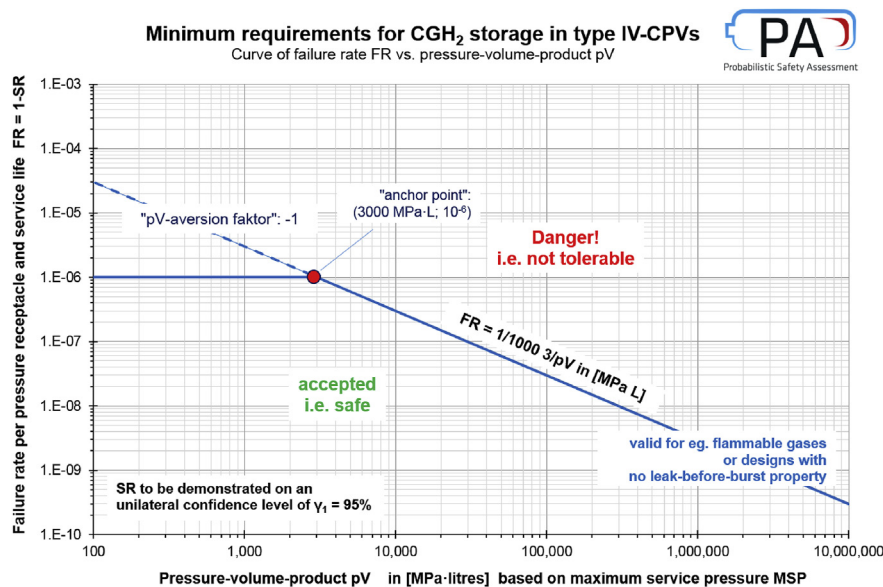


Fig. 4 – FR – pV-diagram for CPVs for hydrogen of BAM [14].

area is anchored at 10^{-5} per year for 10 casualties, which is considered a major accident.

Based on these general aspects, BAM looked for a criterion for consequences that can easily be operated on pressure storage units. Until the year 2001, transport regulations in Europe [16] used the product of pressure and volume of a pressure vessel for determining the approval procedure. From this experience, BAM elaborated a diagram for the acceptance of failure rates for composite pressure vessels (CPVs) as a function of the pressure-volume-product (pV-product) [17]¹. Narrowed down to the special aspects of hydrogen storage stored in CPVs with plastic liner (type IV), this approach leads to Fig. 4. For smaller units, the accepted value starts on a level of $FR = 10^{-6}$ per the entire lifetime of a CPV as it has been adopted from the working party 15 of the UNECE for the special provision SP 674 in the RID/ADR, [16]. At a pV = 3000 MPa L the accepted failure rate FR decreases with a slope of 1/1000 of 3/pV-product (displayed in MPa litres).

In the following section, the combination of probability and consequence is used for validation of the best mode of adequate action.

Validation of the proposed FR-pV curve

The basic scheme to determine the acceptable risk level is to determine the consequence first. After the consequence is known, the appropriate risk level can be read from an F-N-diagram. To define safety in terms of composite pressure vessels, it is necessary to understand the consequence of a failure. Therefore, the worst-case scenario of a bursting pressure vessel shall be examined. Fig. 5 is a diagram that shows the basic concept behind such an examination of the

physically stored energy based on a TNT-model according to [18,19]. The chemical energy (ignition of the released gas) is not considered, which might be acceptable as a first approach for hydrogen. For CNG, LPG and other flammable gases, the chemical energy must be considered.

The event of a pressure vessel burst has two potential effects that could be lethal to people inside of a danger zone around the pressure vessel: the pressure peak of shockwave and fragmentation (i.e. flying splinters). In the ongoing examination of the risk, only the first effect is considered to demonstrate the consequence-based approach. The description of the aspect of flying splinters is still under development. This is much more complicated than the consideration of the pressure wave, and it depends on a lot more of aspects specific to the location of the event. It is out of the scope of this study and will be published later.

The burst of a pressure vessel releases the gas rapidly and creates a shockwave which is potentially lethal. To determine the consequence for a given pressure vessel, the pressure peak of such a shockwave regarding the distance to the blast needs to be determined. In [21] a modified method according to Baker [22] is used to estimate the over pressure of the blast wave in the vicinity of a bursting vessel.

The energy of the physical explosion for the formation of the pressure wave is determined with the thermodynamic availability model. This is a rather conservative approach [23] but is in good agreement with the experimentally-determined curve progressions [20,24,25]. The real gas behaviour is considered by the equations of state of Peng-Robinson or Soave-Redlich-Kwong with the compressibility factor. The maximum overpressure of the blast wave next to the vessel is significantly lower than the burst pressure. An estimation of this pressure is made by the gas dynamic equations (shock-tube equation) [23,24,27].

The curves published by Baker [22] assume a spherical blast wave, which is the case for a spherical vessel that abruptly breaks into many pieces. According to Baker [19], the

¹ In Germany this curve has been used for the service life checks of UN-CPV for transport of dangerous goods according to all relevant regulations (see <https://tes.bam.de/druckgefasse>) since 2014.

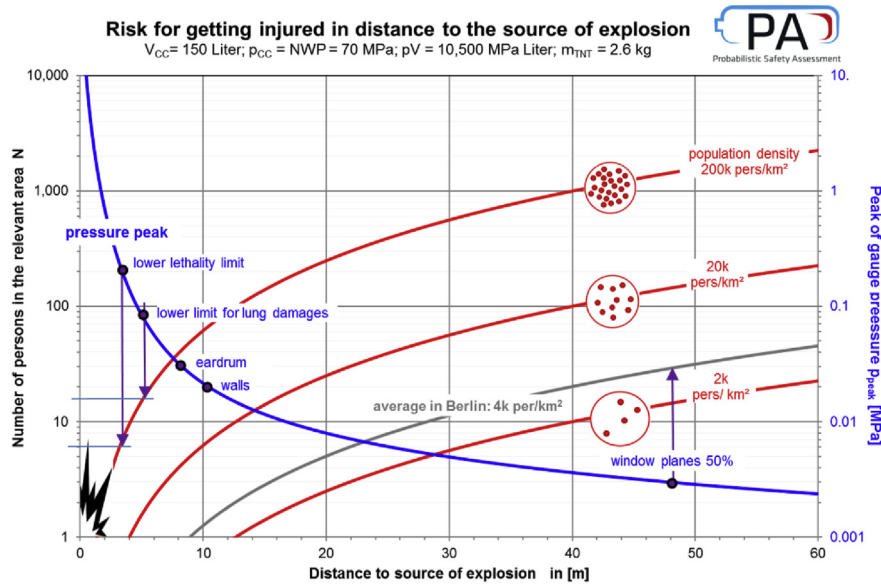


Fig. 5 – Shock wave pressure peak from [17] according to the TNT-model from [15,16].

calculated overpressures for cylindrical vessels must be multiplied by a factor of 4–5 in the nearfield, decreasing with distance to a value of 1.4. This approach has also been adopted in [26] but delivers values that are too large compared to measured values. Geng [28] has carried out comparative calculations of the blast overpressure of a hemispherical pressure vessel in comparison with a vertical cylindrical pressure vessel. The ratio of vessel length to vessel diameter and the burst pressure were varied. The resulting factors are recommended for application in [29] and are also used in this model.

The influence of the different gases transported as dangerous goods is much higher than the influence of the real

gas behaviour discussed in the literature mentioned above. Therefore, the following analysis uses the simpler approach from Brode [30], with which it is possible to determine how many casualties there will be for a given population density [31]. This can be done for different pressure-volume-products (pV-products) and based on this it is possible to generate the diagrams which show the correlation between the pV-product and the lower lethality radius, as shown in Fig. 6.

Fig. 6 shows a pressure wave caused by the rupture of a pressure vessel losing its energy and with the distance to the explosion origin. The pressure peak decreases with this distance. But this decrease depends on the gas properties and is less critical for hydrogen than for most of gases. If a

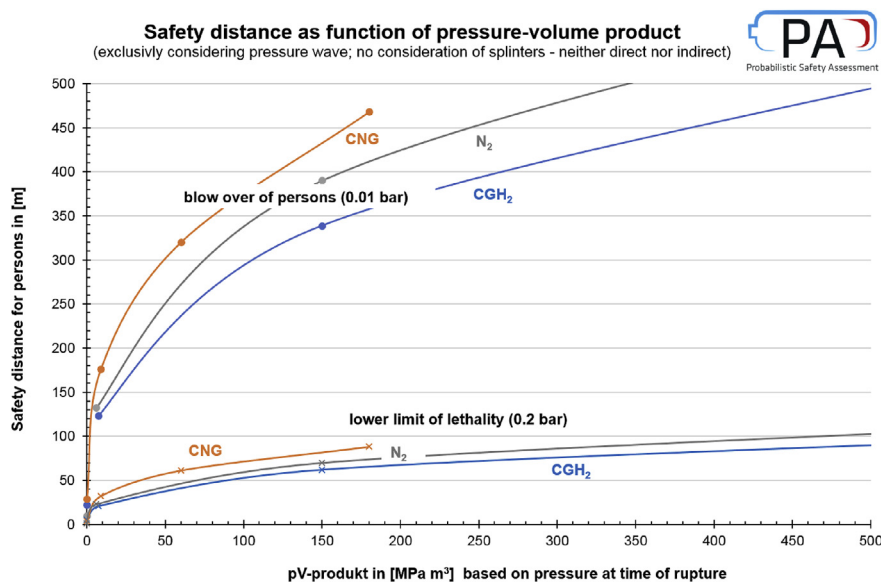


Fig. 6 – pV-product vs. safety distance for different gases according to the model from Brode [30].

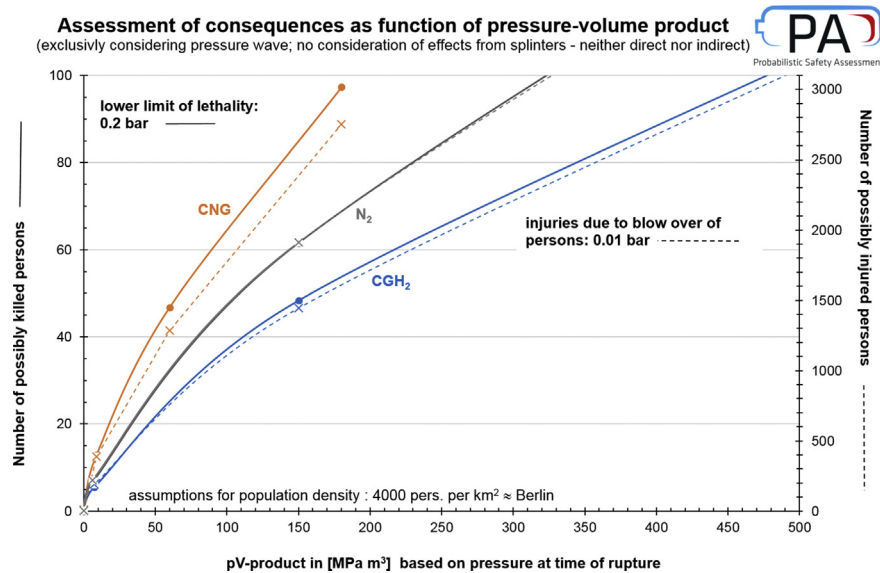


Fig. 7 – pV-product vs. casualty count for different gases (Brode-model).

corresponding population density is added, it is possible to correlate the number of casualties to the pV-product, as shown in Fig. 7. The displayed consequences depend on different pressure levels. Nevertheless, for nitrogen and hydrogen, they behave similar when correlated by a factor. This is a reliable indication that the pV-product is a useful description of consequences. Based on this data, it is possible to determine the consequence for given cylinder designs.

Fig. 7 also shows the behaviour of nitrogen and compressed natural gas (CNG), which has by far the worst consequences caused by a pressure wave of the three gases shown here.

In this example with a population density of 4000 persons per km², according to the red line in the lower part of Fig. 8 a rupture of a pressure vessel with a pV-product of about 100,000 MPa L may lead to a consequence of 40 fatalities, solely because of the blast wave. The same line in the upper part of Fig. 8 shows the accepted FR per lifetime in accordance to Fig. 4. For this example, this result to an interaction of ($N = 40$; $FR = 3 \cdot 10^{-8}$) for pV-product of 100,000 MPa L.

This point ($N = 40$; $FR = 3 \cdot 10^{-8}$) presented in Fig. 8 cannot be allocated in Fig. 3. There, the lower line crosses at $N = 40$ a value for the frequency of failure per year of about $F = 5 \cdot 10^{-9}$ is presented, which is 1/6 of the value in Fig. 8. This significant deviation between Fig. 3 and the proposal presented in Fig. 4 is due to the difference between the definition of F in Fig. 3 and the meaning of FR in Fig. 4. As already mentioned, while F-N-diagrams work with the amount of failures per year, BAM's Fig. 4 is based on the probability of failure (failure rate FR) during the entire life of a CPV. Since these are 15 years or more, a factor of at least 15 must be used in comparing both figures. Without consideration of splinters, BAM's approach thereby stays much more conservative for the transport of hydrogen than the relevant F-N-curve for stationary plants in Fig. 3.

Besides the risk control, there is an additional aspect: the maximum level of consequence. This will be analysed in the next section.

Special aspects of extremely high consequences

On the other hand, the "KALKAR ruling" of the German supreme court (Bundesverfassungsgericht) [32] with reference to Article 2 (2) of the German Basic Law states that a special responsibility for precautionary measures arises from the consequence of a possible damage event. For example, in the case of special consequences, regardless of the level of frequency, a set of rules is required to continuously adapt the safety measures of relevant installations to the SoSe or even the SoSt. This often includes only site-specific manageable measures. This means that above the corresponding potential of a consequence, measures must be taken which go beyond the state of the art or the generally recognized rules of technology. This also means that in these cases, compliance with the rules in terms of testing and approval can no longer be enough. In extreme cases, the necessary additional measures may request actions outside of the field of transport regulations.

According to consequence-probability diagrams (F-N-curves) accepted in several European countries, a catastrophe is said to have occurred in the event of a death toll of 45 or more [20]. The relevant scale that provides this data in the F-N-diagram valid for stationary plants is from "Schweizer Bundesamt für Umwelt, Wald und Landschaft BUWAL" (Swiss Federal Office for the Environment, Forests and Landscape). This is part of a diagram used in the context of the Swiss "Störfallverordnung StFV" (hazardous incident ordinance) [15], presented in Fig. 9. It shows a critical value of 45 fatalities at which the consequence enters the area of a catastrophe.

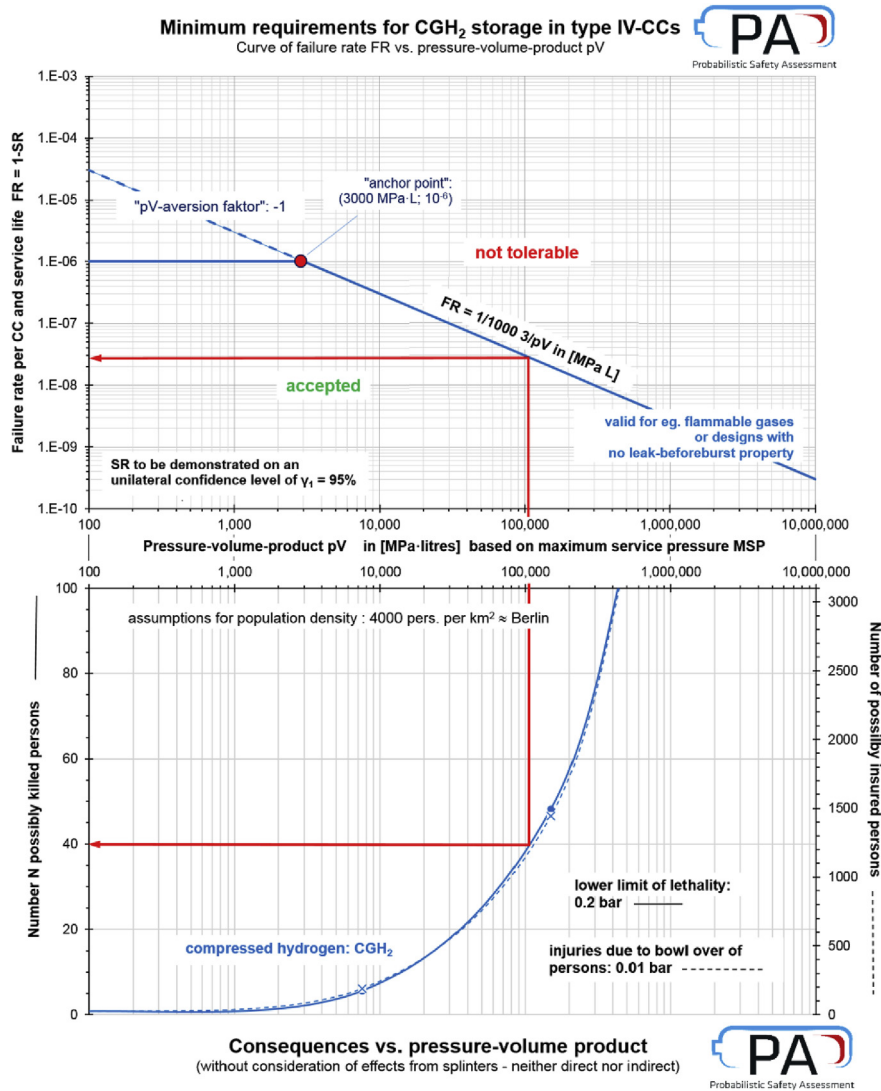


Fig. 8 – The combined usage of an F-pV-diagram with an FR-pV-diagram; cp. Fig. 5.9 in [15].

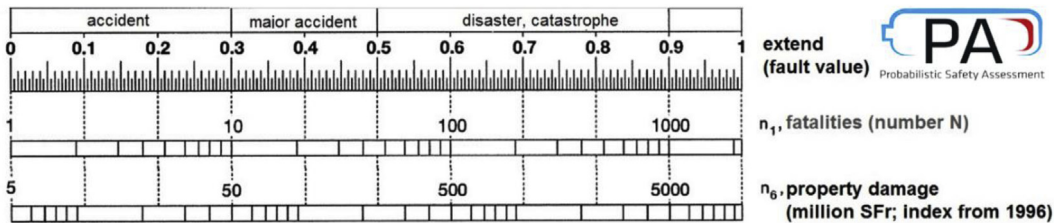
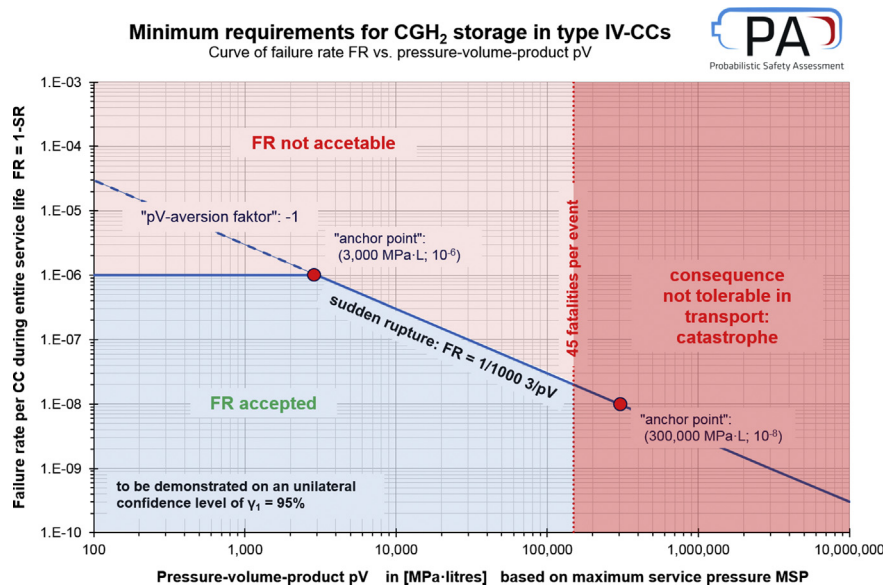


Fig. 9 – Source: RICHTLINIEN (1996) Beurteilungskriterien I zur Störfallverordnung StFV. Bundesamt für Umwelt BAFU, Bern [12]; translated from German.

Such a catastrophic extent of damage with 45 fatalities occurs according to the previous, even more expandable considerations on the consequences in the case of spontaneous bursting of a hydrogen pressure vessel (even without consideration of the reactivity of the stored gas mass) from a pressure-volume product of about 1.5 million bar litres

(150,000 MPa L) when related to the maximum pressure in service (MSP). The maximum service pressure MSP at 65 °C may go up to test pressure (named “PH” according [16,33,34]) for some gases. Since the (nominal) working pressure at 15 °C (PW) is defined as 2/3 of test pressure, a 1 million bar-litres value can be used when referenced to PW.



In view of the currently increasing amount of transported gases and the therefore commercial interest in increasing the capacity of transport units for hydrogen (and natural gas), there is some pressure for changing the current definitions of transport containments for gases with a maximum water capacity of 3000 L to possibly larger volumes. Therefore, the proposal made here is to consider the pressure-volume-product of pressure vessels in transport regulations for gas as a dangerous good.

Fig. 10 reflects that intensive risk management can and must be enshrined in legislation. Nevertheless, there is a limit to the extent of damage (here indicated with the pV-product), which works independently of the probability of occurrence and only because of the possible consequences. Such transports could only be organised under consideration of additional measures like safety distances and route control despite of “accident safety.” This means a certain level of resistance against accidental loads but no freedom from failure (see Fig. 3). This would be associated with e.g. a route to be permitted in advance and considerable monitoring measures.

Since the current transport of gaseous energy carriers would no longer be feasible to the necessary extent in a hydrogen society under these boundary conditions, the working hypothesis to be tested is as follows: Above a certain level of consequence, the measures to be taken to manage the risk of an accident can no longer be regulated (solely) by harmonised technical rules. Further measures (e.g. safety distances, plant-related contingency plans) would have to be taken to control such consequences. Since for none of the mobile usages of pressure vessels, neither for dangerous goods transport nor for vehicles adequate measures can get organised, risk management for mobile units is only manageable and acceptable up to a certain level of consequence.

A new view on risk

The approach shown above for the consideration of risk limits was developed and used for stationary plants. It also utilizes location-based measures for safety surveillance including local emergency plans, which in this form are not applicable for mobile units of comparable consequence potential. An area-wide combination of locally organised measures and massive route restrictions as the normal case for gas powered vehicles would take the idea of mobility ad absurdum and would mean massive restrictions for the placement of fuelling stations supplied by vehicles.

One approach that is very close to the principle of location-based plants is the one currently followed by the Netherlands and under consideration in France. According to this approach, the risks from transport are also considered in relation to the transport routes and spatially resolved risk maps are considered. These would then be used to minimise the risks from transport. Such an approach, however, reaches its limits for cross-border transport if transport routes do not align with comparable routes in a neighbouring country. In addition, such considerations can only be implemented for substances that go from a few starting points to very few destinations. For industrial usage of hydrogen or other gases, a transport with road restrictions might work. But it will limit the transport volume, the number of routes and the possible destinations. No one will be keen on living along such an identified route.

So, the question arises how further risk-controlling measures can be taken in transport. This becomes very important when considering the transport of energy carriers, and especially when aiming to minimise the involvement of many people in a spatial concentration of the vehicle-inherent risk. The means of choice is certainly a

form of route restriction, according to which routes through cities or past major events and meeting points are avoided, unless these are necessary for the direct supply of fuel cells. This, of course, is always within the limits for the individual vehicle described above by the pV-product. However, this is an elaborate, less user-friendly and hardly controllable approach.

When focusing on risk control its essential point must also not be forgotten that by looking at the risk caused by a (stationary) plant, it is always and exclusively bound to a specific location. Such a plant exists only once. The (local) influences of several plants relevant to incidents needs to be considered equally if they are within a wider radius. On the contrary, there are a number of transport events on restricted rail roads (e.g. for chlorine gas). In this case the given rail route represents a linear location for these vehicles. Comparing this to the road transport of e.g. hydrogen, it is not determined how many vehicles pass any point in the road network. The number of vehicles cannot be regulated and follows the market demand for transport services.

However, mobile hydrogen storage systems such as hydrogen transport vehicles are predestined for an approach for an extended consideration of the risk: the description of the task of mobility that can be easily quantified.

In principle, the acceptance of a risk arises from the balance between disadvantage (failure risk) and benefit (economic opportunity). In this meaning the purpose can be assigned to the vehicle: The transport of people or carrying goods. The transport performance corresponds to either passenger kilometres or tonne-kilometres.

$$Benefit_{transport} \equiv \frac{mass \cdot distance}{time} = \frac{m \cdot d}{t} \quad (1)$$

The risk consists of the combination of the frequency of an event and the consequence of that event (cp. [9]):

$$Risk_{transport} = Frequency(event) \cdot Consequence(event) = F \cdot C \quad (2)$$

The frequency is the number of events per time, while the consequence in insurance can always be expressed in costs.

$$Risk_{transport} = \frac{number\ of\ events}{time} \cdot Consequence\ in\ costs = \frac{n}{t} \cdot C \quad (3)$$

The cost-benefit analysis (advantage vs. disadvantage; i.e. chance vs. risk) could thus be derived from a comparison of transport performance during a vehicle cycle or the life of a pressure vessel with the risk resulting from its use. In most

simple cases, the opportunity-benefit balance can be presented as a ratio:

$$Chance - Risk\ analysis\ (transport) : \frac{Risk}{Benefit} = \frac{n \cdot c}{m \cdot d} \quad (4)$$

Example of analysis: tube trailer vs. battery vehicle

As an example of analysis, two different battery vehicles (as defined in section 1.2.1 of the relevant regulation [16]), both transporting a maximum amount of 900 kg hydrogen, are compared. Battery vehicles with seamless steel tubes built from several horizontally arranged tubes (compare Fig. 11 left) are often called “tube trailer,” while an assembly from considerably more, smaller and vertically arranged CPVs (see Fig. 1 or compare Fig. 11 right) are usually called battery vehicles in Europe.

An assumption for the following analysis is that a failure of one of the CPVs does not lead to the simultaneous failure of an adjacent CPV. This means a time delay of pressure waves in the case of a cascading failure that is assumed here as consecutive and not accumulating pressure waves. Details on this will be part of future studies. As opposed to the probability of failure, the consequence of a failure does not depend on the number of individual elements under this assumption. Rather, the consequence of failure depends exclusively on pressure and volume of the CPVs mounted on a hydrogen transport vehicle (HTV), while the number of CPVs influences the probability of failure. Consequently, the total volume of transported hydrogen on an HTV (given by the number of CPVs, their volume and pressure level) influences the risk of transport.

An example analysis of this is shown based on the red line from Fig. 8. This figure is based on an element-related criterion, as is currently common practise in the corresponding regulation [13,33,34]. The used CPV is a legally called “tube” with 2000 L and 500 bar maximum service pressure, which means a pV-product of 100,000 MPa L. The tube trailer consists of 16 CPVs.

According to Figs. 8 and 10, the corresponding acceptable failure rate of each CPV during its 25-year long life is $3 \cdot 10^{-8}$. Since the failure of the individual pressure vessel during normal operation is almost independent, it is assumed that the failure probability of one of 16 CPVs in the vehicle is $4.8 \cdot 10^{-7}$ in 25 years or $1.9 \cdot 10^{-8}$ per year. According to the scale



Fig. 11 – Conventional steel-tube trailer (left) and battery vehicle with 200 CPVs for hydrogen (right).

in Fig. 9 from CH [15], the consequence of 40 deaths is comparable with an economic loss of 200 Mio SFr (Swiss Franks), which equals 175 Mio EUR.

This can be used for deriving the risk in EUROS posed by the tube trailer (TT) as a complete vehicle:

$$\text{Risk}_{\text{TT}} = 1.9 \cdot 10^{-8} \cdot 1.75 \cdot 10^8 \text{ € p.a.} \approx 3,4 \text{ € p.a.} \quad (5)$$

Assuming a gas density for compressed hydrogen of 28 kg/m³ at T_{max} = 65 °C and MSP = 500 bar (see [20]), a total mass of hydrogen per element (2000 L) of 56 kg and 900 kg of hydrogen for the complete TT-vehicle is obtained. It is further assumed that an annual mileage of 50,000 km will be achieved. This allows the benefit of usage to be quantified as transport performance:

$$\text{Benefit}_{\text{TT}} \equiv 900 \text{ kg} \cdot 50000 \text{ km p.a.} = 4.5 \cdot 10^4 \text{ t} \cdot \text{km p.a.} \quad (6)$$

This results in a cost-benefit comparison, which could also be interpreted as a chance-related risk, referred to here as transport-specific risk value (TRV):

$$\text{TRV}_{\text{TT}} : \frac{\text{Risk}_{\text{TT}}}{\text{Benefit}_{\text{TT}}} \approx \frac{3.4 \text{ €}}{4.5 \cdot 10^4 \text{ t} \cdot \text{km}} \approx 75 \frac{\text{€}}{\text{Mio t} \cdot \text{km}} \quad (7)$$

This characteristic value does not reflect the costs of operation, etc., but the costs that the general public (may) incur on average due to the operation of a battery-powered vehicle as a result of failure if approval and monitoring are carried out in accordance with the above-mentioned limit values. A reverse consideration of this characteristic value of the tube trailer leads to a different characteristic that can be described as risk-specific transport performance (RTP):

$$\text{RTP}_{\text{TT}} : \frac{\text{Benefit}_{\text{TT}}}{\text{Risk}_{\text{TT}}} \approx \frac{4.5 \cdot 10^4 \text{ t} \cdot \text{km}}{3.4 \text{ €}} \approx 13\,400 \frac{\text{t} \cdot \text{km}}{\text{€}} \quad (8)$$

If the same amount of gas is now transported with a battery vehicle (BV) with 200-L CPVs, 160 elements (pV-product = 10 000 MPa L; 7 deaths or 35 million SFr = 31 million EUR) must be used for the storage of the total amount of gas. The minimum survival probability required according to Fig. 3, Figs. 8 and 10 is $3 \cdot 10^{-7}$. The assumed service life is 25 years as above. This results in a failure rate for the battery vehicle of $4.8 \cdot 10^{-5}$ in 25 years or $1.9 \cdot 10^{-6}$ per year.

If one now calculates the risk/chance-balance for this battery vehicle (BV) analogously, one obtains:

$$\text{Risk}_{\text{BV}} = 1.9 \cdot 10^{-6} \cdot 31 \cdot 10^6 \text{ € p.a.} \approx 60 \text{ € p.a.} \quad (9)$$

$$\text{Benefit}_{\text{BV}} \equiv 900 \text{ kg} \cdot 50000 \text{ km p.a.} \approx 4.5 \cdot 10^4 \text{ t} \cdot \text{km p.a.} \quad (10)$$

$$\text{TRV}_{\text{BV}} : \frac{\text{Risk}_{\text{BV}}}{\text{Benefit}_{\text{BV}}} \approx \frac{60 \text{ €}}{4.5 \cdot 10^4 \text{ t} \cdot \text{km}} \approx 1300 \frac{\text{€}}{\text{Mio t} \cdot \text{km}} \quad (11)$$

$$\text{RTP}_{\text{BV}} : \frac{\text{Benefit}_{\text{TT}}}{\text{Risk}_{\text{TT}}} \approx \frac{4.5 \cdot 10^4 \text{ t} \cdot \text{km}}{60 \text{ €}} = 760 \frac{\text{t} \cdot \text{km}}{\text{€}} \quad (12)$$

Although each individual CPV is within the risk range accepted for the pV-product of the individual element, the risk values of both analysed vehicles vary considerably under the assumed boundary conditions. This means that the last analysed battery vehicle with 160 smaller vessels is significantly less effective (more than 15 times lower risk-specific

transport performance RTP) concerning its chance-related risk than the vehicle with 16 considerably larger elements. The statistical influence of the higher number of sealings, valves and pipes, which increases the probability of small leaks in the battery vehicle compared with the tube trailer is not considered here.

This difference in risk efficiency is also shown in Fig. 12. The individual elements (blue dots) in both vehicles are far within the accepted risk range. But irrespective of the mileage, the risk for both vehicles moves due to the total number of elements into the critical range and should therefore be further reduced according to “as low as reasonably practicable” (ALARP).

Effects of appropriate actions for achieving full acceptance are indicated by the red arrows. This translates to a modification of the element design and manufacturing in such a way that the failure rate under the conditions of normal use decreases to a level appropriate for the whole vehicle. The shown reduction of the failure rate of individual elements results in both cases in vehicles that are exactly on the acceptance limit. The demonstration of extremely low failure probabilities of large and thus expensive CPVs tend to be less reliable than safety assessments of smaller CPVs. This does not mean that the safety level is lower but that the statistical uncertainty in test results is higher. For this reason, the use of smaller and more frequently produced CPVs as elements is generally preferred.

Nevertheless, it should be noted that under the assumptions that a) only one element fails at a time and b) the probability of failure is proven to be reliable even for large CPVs, the vehicles with the larger elements for the same transported mass of hydrogen and travel distance represent the more efficient solution. This is indicated in Fig. 12, with the lower correction effort indicated by shorter arrows.

This does not mean “the larger the better”. Depending on the individual safety aspect there will be different optimal sizes, either objectively or just with respect to the demonstration of the safety level.

Verification of probability of failure

The approval as well as the associated determination of the service life of a “composite pressure receptacle” (official designation in the relevant transport regulations) is carried out on a pilot series before actual production begins. In order to do so, service life ageing must be simulated, since the safety of pressure vessels at the end of their service life still needs to be guaranteed. Simulating a CPV life in a short time span requires extensive knowledge of subsequent loads and adequate time-lapse methods. There is no scientific evidence that the hydraulic accelerated stress testing invariably equals the ageing of pressure vessels in real use [17]. Since these aspects cannot be answered in one step, the evaluation of new test samples is considered here first.

Currently, the minimum burst pressure is being intensively discussed within the framework of the revision of GTR No. 13 [35]. Regarding the aspect of burst testing, the ECE R 134 as the European adoption of GTR No. 13 requires destructive batch tests (one burst test per manufacturer batch) and a non-

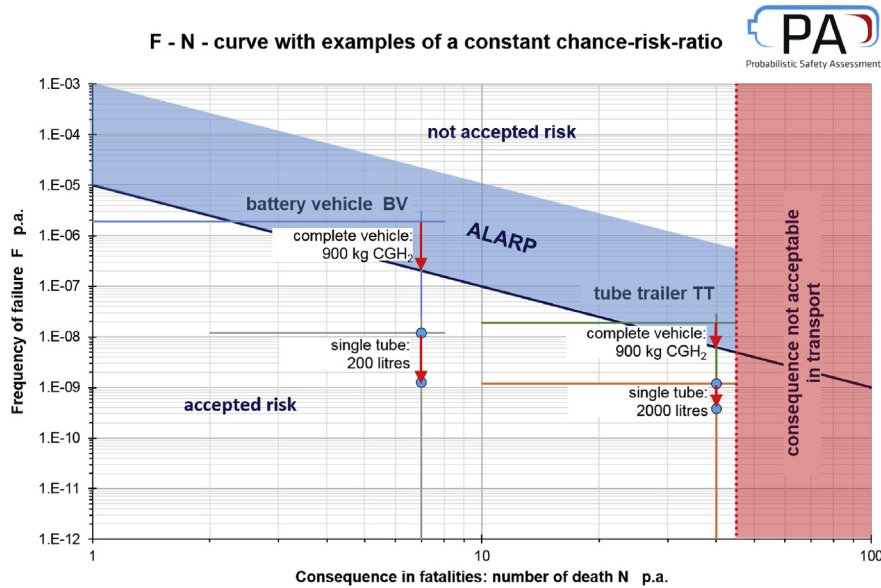


Fig. 12 – Risk-oriented correction of accepted failure rate for CPV-elements based on the vehicles' properties up to catastrophic consequences.

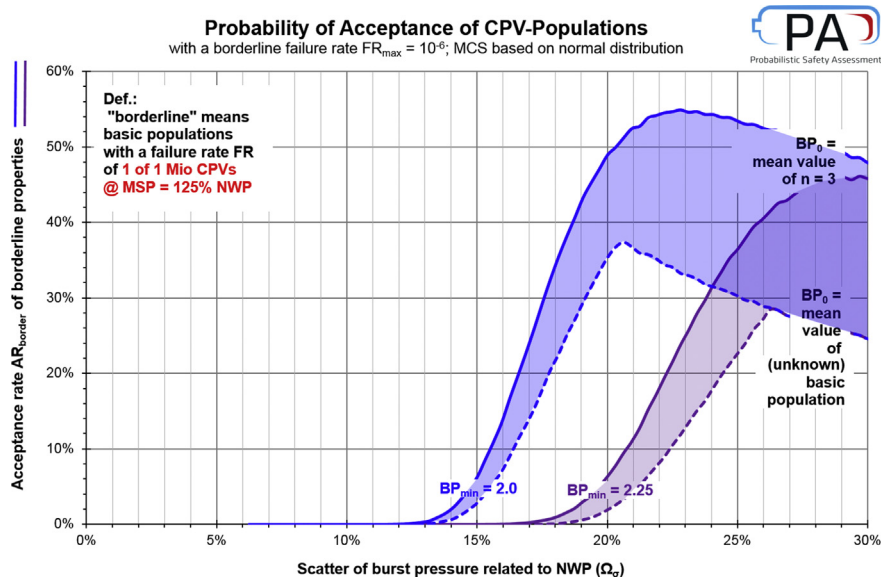


Fig. 13 – Dependency of the probability of accepting a design type from the scatter of production and the minimum required burst pressure.

destructive initial test performed on each pressure vessel as the last part of production by the manufacturer. In the latter, the vessel is pressurized to the test pressure PH to ensure the burst strength is over the maximum pressure during operation. For hydrogen, the test pressure PH is equal to 150% the nominal working pressure (NWP) or 120% of the maximum service pressure (MSP). The maximum service pressure is the pressure level which might be reached when filling a vessel due to thermal expansion of the gas up to 85 °C. There are a number of other tests, but these are not as much aimed at initial strength as at various forms of possible ageing and damage during operation.

In the course of the revision of GTR No. 13 Phase 2 [36] a decision has been made to reduce the minimum burst pressure from 225% to 200% of the NWP. It is worth mentioning that the author has argued against this reduction in the committee [37]. A minimum burst pressure of 2 times NWP corresponds to only 160% of the maximum service pressure expected during service. The reason for the rejection is not the minimum burst value per se, but the parallel lack of a suitable limitation of the maximum scatter of the burst strength. For this purpose, Fig. 13 shows the influence of scatter on the acceptance rate AR, which means here the maximum probability of accepting populations with a failure rate of more than 1 in 1 million,

which are considered to be on the border between the defined safety and danger. Hereafter these populations are referred to as borderline populations. The background to the analysis can be followed in Chapter 5.2 from [20] (cf. Fig. 5.25).

Fig. 13 and the following analyses were developed within the framework of the Horizon 2020-project TAHYA [38], funded by FCHJU. It shows the rate of accepted burst test samples of normally distributed populations. The populations are characterized by a specific combination of a mean value and standard deviation which result in a constant failure rate of 1 in 1 million against the MSP. As a measure of scatter, the standard deviation is used in this diagram to represent the population, as the corresponding mean value can be derived from the given failure rate.

This diagram is used in this paper to show that the acceptance rate for unsafe CPV design types is currently too high. Everything over 5% (typical confidence interval) should be avoided by a regulation. At very high scatter levels, the acceptance rates drop slightly because of the scatter criterion around BP_0 stated in the GTR No. 13. This, however, is not within the scope of this paper.

While the right set of curves is based on a minimum burst value of 2.25 NWP, the left set of curves shows the AR for a reduced minimum burst value of 2.0 NWP. The two upper limit lines show the result when the required midpoint burst pressure BP_0 is determined directly from the required sample of three CPVs. The lower pair of lines represents the ideal but impossible case, where the true mean of production is known and stated by the manufacturer as the BP_0 . In all cases, it can be seen that for high levels of scatter, the acceptance rate of unsafe pressure vessel populations is very high. Thus, the scatter is not sufficiently restricted by the regulation. The required minimum burst pressure in the context of the design type approval is in the centre of importance as it is currently attributed to be. The scatter of the burst pressure in production is of much higher significance in practice, which the following analysis also confirms.

The central question stands whether the produced population of CPVs still meets the safety requirements which have been passed in the type approval process. The statistical properties of the population from the large-scale production may differ considerably from those of the pre-series on which the type approval is based.

The so-called “batch test” (test of production batches) is also based on the minimum burst pressure from the design type testing. For each production batch not being larger than 200 CPVs, one CPV is pressurized until burst having to meet this minimum burst value so that the relevant production batch can be released and delivered. The aim of this test is to ensure consistent quality of the CPVs in production. As shown in Fig. 14, the number of CPVs tested per produced batch has an influence on the scatter of the individual sample evaluation. However, the probabilities of acceptance determined as an average of the various ran simulations is a function of the standard deviation of the population, which does not depend on the number of CPVs tested per produced batch. It is assumed here that there is no manufacturing defect in populations meeting the failure rate criterion of one failure at MSP of 1 Mio CPVs (borderline populations).

In any case, a manufacturing defect in the batch should be easier to detect through non-destructive testing than by testing only one CPV of the production batch. Thus, the so-called batch tests lose their original meaning. If one rightly continues to assume that manufacturing defects only affect individual CPVs of the batches, it is not likely to find an individual manufacturing defect anyway. With the current concept of testing 1 in 200 (burst tests), success is almost independent of the minimum burst pressure required by the regulations. This leaves one aspect of batch testing that is probably of the greatest importance today: Depending on the mean value, scatter and statistical distribution of the burst strength of a production, a certain percentage of CPVs are rejected - even if the production is free of critical defects. Each rejected CPV represents an economic loss, so it can be assumed that the portion of rejected CPVs will be reduced as

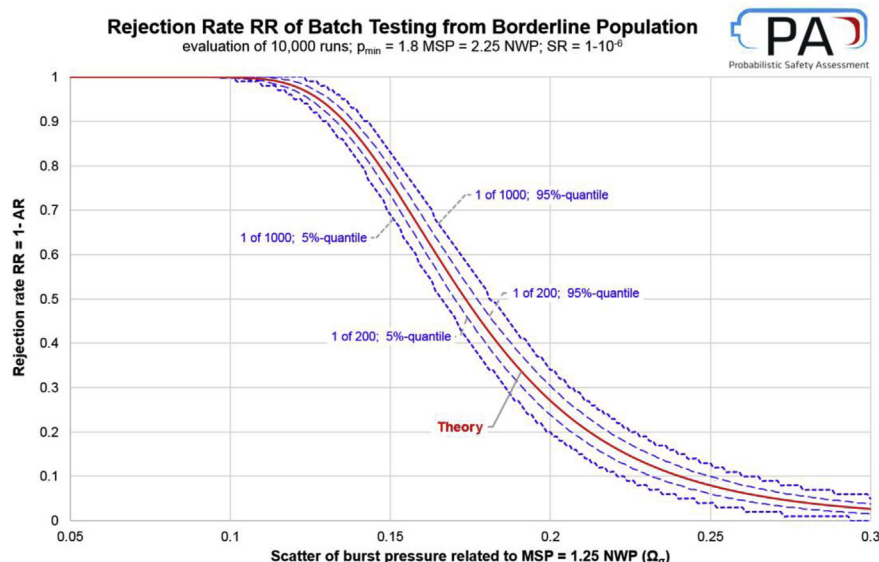


Fig. 14 – Influence of batch size on the accuracy of rejecting borderline populations.

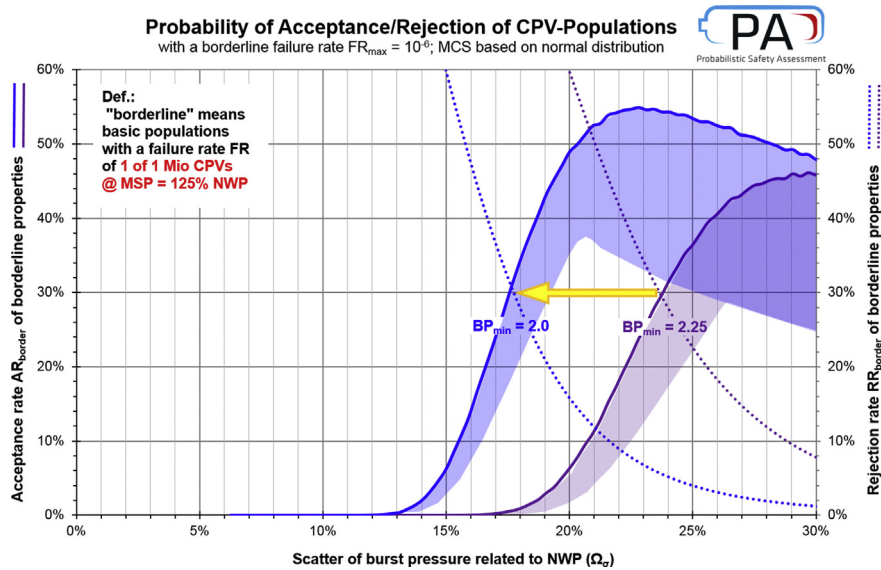


Fig. 15 – Influence of the minimum required burst pressure on the ratios of accepting a design type and rejecting a design type over the production scatter.

far as possible by design and quality assurance. Accordingly, the effect of the explained reduction of the minimum burst pressure has a second aspect that is displayed in Fig. 15. It shows the curve of rejected production batches as rejection rate RR, in addition to Fig. 14. Since the RR of borderline populations decreases to acceptable values at relatively high scatter values, it is expected that in the practice of mass production, avoiding batch rejection may play a more important role than the design type requirement.

The central aspect of the analysis, however, is the question of guaranteeing safety. To analyse this, the combinations of mean strength and scatter of basic populations are again

taken as an example, with a probability of failure in new condition of 1 in 1 million CPVs.

Due to the nature of the minimum burst condition, the rejection rate is extremely high at low scatter. Accordingly, these high-quality productions with small scatter must have unnecessarily high average values in order not to be rejected. Thus, the curves of rejection rate (right scale) come from above (cf. Fig. 14) and cross the lines of accepting populations introduced in Fig. 13 as the scatter of the borderline population increases.

To the left of the intersection points, the required mean values are unnecessarily high, while to the right the mean

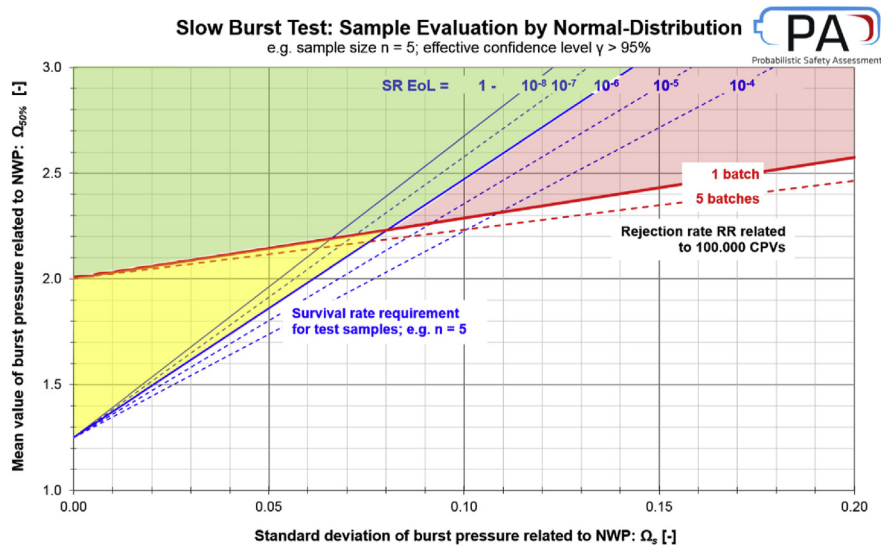


Fig. 16 – Areas of unacceptable approval (red) and unnecessary rejection of designs (yellow) in the sample performance chart of BAM. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

values are too low to keep the acceptance of borderline populations at 5% or lower. This 5% equals a confidence level in test results of 95%. The reduction of the minimum burst pressure does not change the character of this dilemma. It only shifts the problem to lower burst values, thus increasing the ratio of productions that are wrongly judged “safe” by this criterion. This is illustrated in Fig. 16. Since the rejection rate resulting from minimum burst pressure criterion in Fig. 16 is much flatter than the probabilistic safety criterion according to BAM-GGR 022 [39], there are 4 areas that should be evaluated separately. White and green mean that the sample results belonging to the populations are not acceptable (white) or are beyond doubt safe and therefore clearly accepted (green). But more interesting are the yellow and especially the red areas. The red area is acceptable according to the reduced minimum burst pressure, but not acceptable according to the criterion of the failure probability considered here as safety criterion: not more than 1 failures per million CPVs. On the other hand, the yellow area represents an area that leads to unnecessary material expenditure for meeting the minimum burst requirements while these populations are probabilistically safe.

In view of the special importance of tests in production surveillance, a proposal is made to change the requirements for batch testing. On the one hand, the statistical properties of production should be monitored by always combining 5 running batches respectively with their 5 burst results into one group. A continuous evaluation of the resulting sample properties should follow according to the approach shown in Fig. 16 or in BAM-GGR 021 [17], including the monitoring of trends over the production period. In addition, each individual batch test result can be evaluated for its properties as an outlier/early failure, which in combination with non-destructive testing methods, i.e. acoustic emission during the initial test [40] would lead to a better detection of manufacturing defects. In return, the criteria “minimum burst strength” for individual manufacturer batch testing required today could be dropped.

Conclusions and summary

It has been shown that safety requirements related to individual CPVs come to their efficiency limits when the number of vehicles for the supply of hydrogen filling stations and the amount of transported hydrogen increases. This is similarly valid for all gases used as energy carriers, even for CNG or LNG, and for the conventional approach of minimum strength requirements, such as minimum burst ratios. Even the probabilistic approach (PA) fails if it deals with individual pressure vessels and not with the properties of the whole assembly. The design of a transport vehicle according to the number of mounted pressure vessels and the risk limits for these vessels has a considerable influence on the overall risk.

Currently we are experiencing the period of formation of the delivery system for hydrogen supply of filling stations requires a more developed system of risk check and control. Currently, neither the acceptance of the hydrogen economy is developed, nor failure statistics can be used

for improvement of an upcoming system. This leads to the conclusion that a risk-specific criterion should be required for the design of transport vehicles. At least risk limits should be set for large transport vehicles or multiple-element gas containers (MEGCs; cp. UN-Model Regulations [22]), which have high potential for consequence. At the same time, any approach comparable with the regulations for stationary plants is not enough in the case of very high consequence potentials of individual vehicles. This lack increases in case of an enormously increasing number of vehicles required for the total transport volume.

A challenge for the improved safety approach is the effort required to prove the required reliability values, e.g. according to BAM's PA. The verification of a low failure probability, as required for larger units, is considerably more complex and, due to the higher verification objective, also less resilient. For this reason, with a view to the load-bearing capacity of the data on the pressure vessels on a vehicle, elements from mass production would always tend to be preferred, and thus smaller pressure vessels.

When combining all these aspects, there are six conclusions to be made.

1. It is necessary to combine the minimum requirement for the failure rate of each individual mounted pressure vessel with the total risk resulting from each vehicle concept.
2. Accepted risk limits depend on the number of vehicles. This means the risk limitation shall be based either on the total number of events per year over all vehicles running (e.g. nationally) or, with respect to the risk to society, at least on the frequency for taking individual routes by such transports.
3. In principle, the maximum accepted failure rate of a vehicle should be comparable with the most risk-chance-efficient design type of a hydrogen transport vehicle (consequence per ton-kilometres).
4. Criteria should be added to regulations, codes and standards that take effect as a consequence limiter. They shall aim on the maximum accepted consequence with respect to the range of measures that can be regulated by international transport regulations.
5. Beside international transport regulations, additional actions on a national level may be considered and installed for the primarily national organised distribution transport of energy carrier; such as e.g. additional requirements for the driver, special equipment for the fire brigades along the main routes, additional equipment on the vehicles (automatic brake assistance) etc.
6. Strength data to be generated during the mandatory batch testing are available for free and should be evaluated statistically. This information should be used as input for a probabilistic quality surveillance of pressure vessel production, and would give statistically reliable basis for safety assessment.

Some of these measures enter a new terrain of assessment. Nevertheless, the proposed measures should be considered for balancing the new terrain of potential risks in road transport. This is necessary in order to not

jeopardise the acceptance of gases as energy carriers, particularly hydrogen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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