

SAFETY CRITERIA FOR THE TRANSPORT OF HYDROGEN IN PERMANENTLY MOUNTED COMPOSITE PRESSURE VESSELS

Mair, G.W.¹, Wang, B.² and Saul, H.³

¹Containment Systems for Dangerous Goods, BAM, Unter den Eichen 44-46, 12203 Berlin, Germany, Georg.Mair@bam.de

²Containment Systems for Dangerous Goods, BAM, Unter den Eichen 44-46, 12203 Berlin, Germany, Bin.Wang@bam.de

³Containment Systems for Dangerous Goods, BAM, Unter den Eichen 44-46, 12203 Berlin, Germany, Herbert.Saul@bam.de

ABSTRACT

The recent growing of the net of hydrogen fuelling stations increases the demands to transport compressed hydrogen on road by batterie vehicles or tube-trailers, both in composite pressure vessels. As transport regulation the ADR is applicable in Europe and adjoined regions and used for national transport in EU. This regulation provides requirements based on the burst pressure of each individual pressure vessel, regardless the capabilities of the transported hydrogen and relevant consequences resulting from worst case scenarios. In 2012, BAM (German Federal Institute for Materials Research and Testing) introduced consequence-dependent requirements and established them in national requirements concerning the “UN service life checks” etc. to consider the transported volume and pressure of gases. However, this results in a stringent requirement in case of using large pressure vessels (so called “tubes”) on vehicles. In the studies presented here, the safety measures for hydrogen road transport are identified and reviewed through some safety measures from some countries like Japan, USA and China. Subsequently, the failure consequences of using trailers, the related risks and chances are evaluated. Finally, a chance-related risk criterion is suggested to add into regulations and consequently to be defined as safety goal in standards for hydrogen transport vehicles and consequently for mounted pressure vessels.

1. INTRODUCTION

In the second decade of the 21st century we experience currently an early stage of the usage of hydrogen fuel cell vehicles (HFCV), which is combined with road transport for the delivery of compressed gaseous hydrogen (CGH₂). This way of gas transport is an attractive and economical option due to the still wide-meshed net of filling stations and the relatively low capacity of installed infrastructure, [1]. The increase of the amount of transported hydrogen on road and the developments of new designs and materials requires the current regulations, codes and standards (RCS) to be improved quickly to 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, comprehensive experiences is needed.

Based on the experience, the appropriate test procedures and acceptance criteria can be defined. In Japan, New Energy and Industrial Technology Development (NEDO) conducted a research project called “Regulation Reviews concerning Construction and Operation of Hydrogen Stations”, [2]. Among this research project, Kawasaki Heavy Industries has 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. qualified driver, predetermined route and frequent inspections for leakage and over pressure. In addition, they developed a design concept to enhance the safety measures including vibration and collision tests to prevent leakage of the pressure vessels, valves and piping.



Figure 1: State-of-the-art vehicle for the transport of hydrogen in central Europe, based on CPVs

Safety measurements for the two mobile hydrogen filling stations operating during the Expo 2010 in China provided another example for dealing with the equipment for hydrogen, including transport vehicle. K. Sun et al. (2014), [3] 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 the operation during the World Expo including the safety for transport vehicles. F-N curves are used to determine the accepted probability of failure according to the social risks. 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, [4]. The risk acceptance criteria for hydrogen refuelling stations are also referenced to EIHP2 project.

Besides the risk analyses carried out in [3], an efficiency study of using composite tube trailer to transport the hydrogen gas is done in USA, [5]. A model is 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 hold higher payloads compared with the configurations with smaller numbers of large pressure vessels.

All the three examples from Japan, China and 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 transportation of hydrogen. In the next, it will be presented, why is necessary to introduce a new way of considering and describing the safety goal of regulations and codes or standards referenced in regulations.

1. PURPOSE OF REGULATIONS

To achieve the safety in hydrogen transport needs the legally binding criteria for approval and usage of transport vehicles. Therefore, the usage of equipment for the transport of dangerous goods is generally forbidden, with the exception clause of an approval in accordance with relevant regulations, technical codes and standards (RCS).

Determination of the legal basis is the sovereign task of the state or the community of states. International conventions and EU directives acquire the force in individual EU member countries by national laws and ordinances. This mandatory process of incorporating international or European rules into national law is necessary and valid for usage on each individual sovereign national area. Nevertheless, those national ordinances and laws usually refers to the internationally harmonised regulations, which provides all the technical details.

To provide every citizen a strong legal basis for his 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. [6]). As shown in Fig. 2, what once corresponded to the SoST will later correspond to the SoAT or the SoSE.

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 aiming at ensuring the citizens' right to health with a reasonable effort. Regulators follow the basic rules of comparativeness to manage appropriate measures.

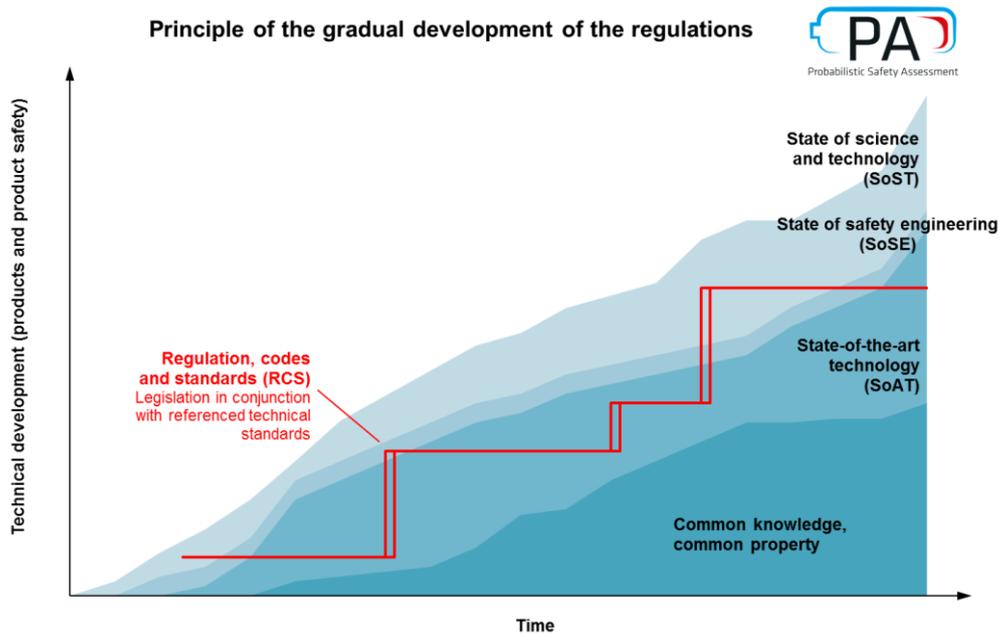


Figure 2: Continuous development of the technology and the step-by-step updating of the law, cp. [7]

Regulations for the transport of dangerous goods are periodically revised at intervals of 2 years and adjusted to the SoAT/SoSE or SoST considering the effectiveness of a measure and economic expenditure. The implementation specific to the mode 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 (cp. [8]).

What is approved in Europe according to such a regulation is considered as safe. Thus, these regulations or the acceptance criteria for approval according to regulations define the level of safety in the relevant area. Therefore, it is to explore the significance of safety and the approach to the definition of safety.

Based on these customary processes of well organised committees and panels there is an increasingly critical effect resulting from the velocity of technology development. The cycles are becoming shorter while the resulting steps of development are increasing. Thus, has brought us to a situation that means a tougher work to improve RCS for existing technologies while adequate regulations for new technologies are more and more fare behind the market and public needs.

The way out could be a more general understanding of safety and a switch from rules focussing on technical measures to rules providing general approaches for 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, regulations determine the level of risk that deems to be acceptable for a technology. Then consequently in terms of work-sharing, codes and standards describe how the demonstration of guaranteed survival rate and maximum consequence shall be performed.

2. HOW TO DESCRIBE SAFETY

To evaluate new developments or new technologies, a minimum of experience with this technology is needed. This enables to determine appropriate test procedures and acceptance criteria. These acceptance criteria traditionally refer to the minimum wall thickness and a hydraulic pressure proof test [9]. 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 (cp. e.g. [10]).

However, the technological development is progressing at an ever-increasing pace. This means that the time span in which the 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 the 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, [11]. It is a risk-based interpretation of safety, which will be explained in more detail here.

The status of safety is achieved when the actual risk during the usage of a technique is below the accepted risk level. Otherwise the status of danger is present. The limits of risk acceptance are usually described in the so-called F-N-diagrams. One set of values widely accepted in Europe is presented in Fig. 3. It is based on a F-N-diagram, which is deduced from the one from Switzerland (see [12]) and additional aspects from the Netherlands. It shows an acceptance level for the failure rate per year and plant. F decreases with the increase of consequence in terms of number of fatalities or property damage.

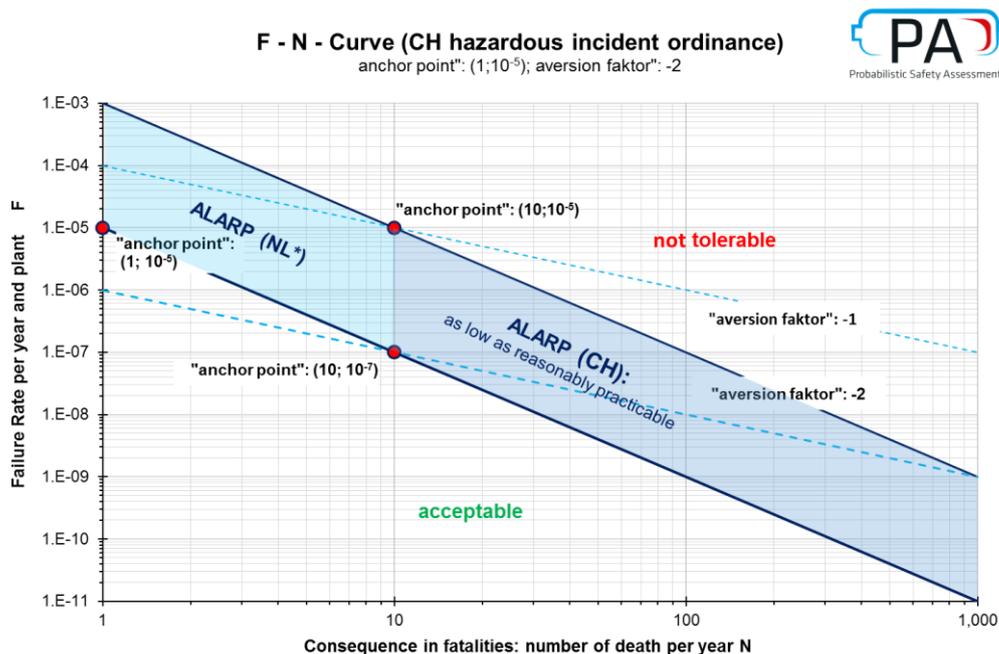


Figure 3: F - N - curve as used in Europe (cp. Fig 5.2 in [15])

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

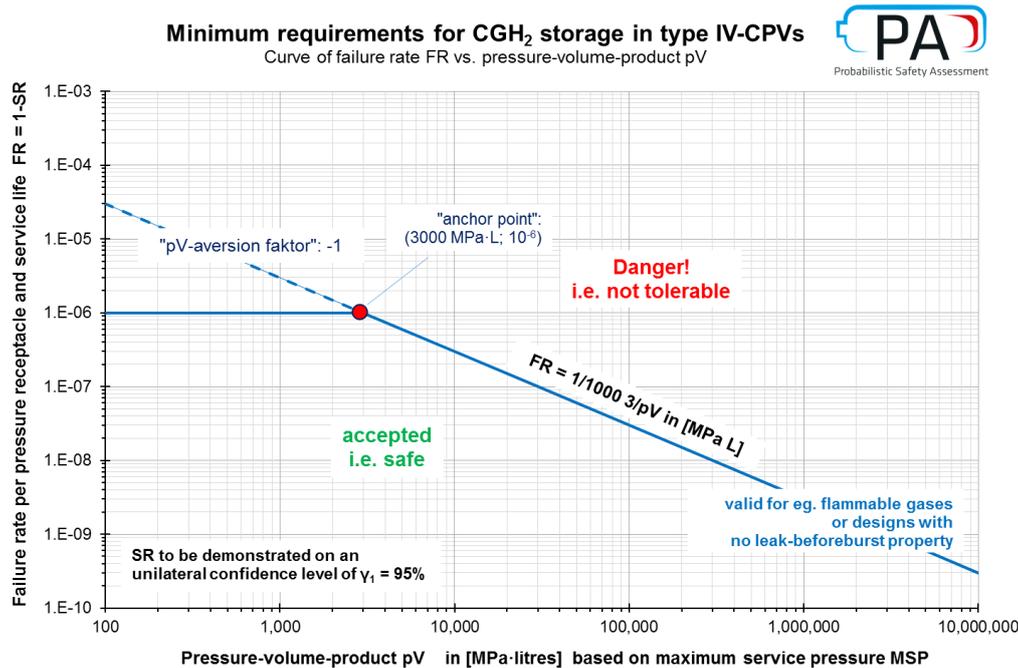


Figure 4: FR – pV-diagram for CPVs for hydrogen of BAM

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 [13] used the product of pressure and volume of a pressure vessel for classification of the level of effort needed for approval. 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) [14]¹. The narrowing to the special aspects of hydrogen storage stored in CPVs with plastic liner (type IV) leads to Fig. 4. For smaller units the accepted value starts on a level of $FR = 10^{-6}$ per the entire life time of a CPV as it has been overtaken from the working party 15 of the UNECE for the special provision SP 674 in the RID/ADR, [13]. At a $pV = 3000$ MPa litres the accepted failure rate FR decreases with a slant of $1/1000$ of $3/pV$ -product (units [MPa litres]).

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

3. 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 a F-N-diagram. To define safety in terms of composite-cylinders, it is necessary to understand the consequence of a failure. Therefore, the worst-case scenario of a bursting pressure vessel shall be examined. In Fig. 5 is a diagram that shows the basic concept behind such an examination.

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 work. It is much more complicated than the consideration of the pressure wave, and it depends on a lot more of aspects specific to the place of event. It is out of the scope of this study and will be published later.

¹ Since 2014 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/druckgefaesse>).

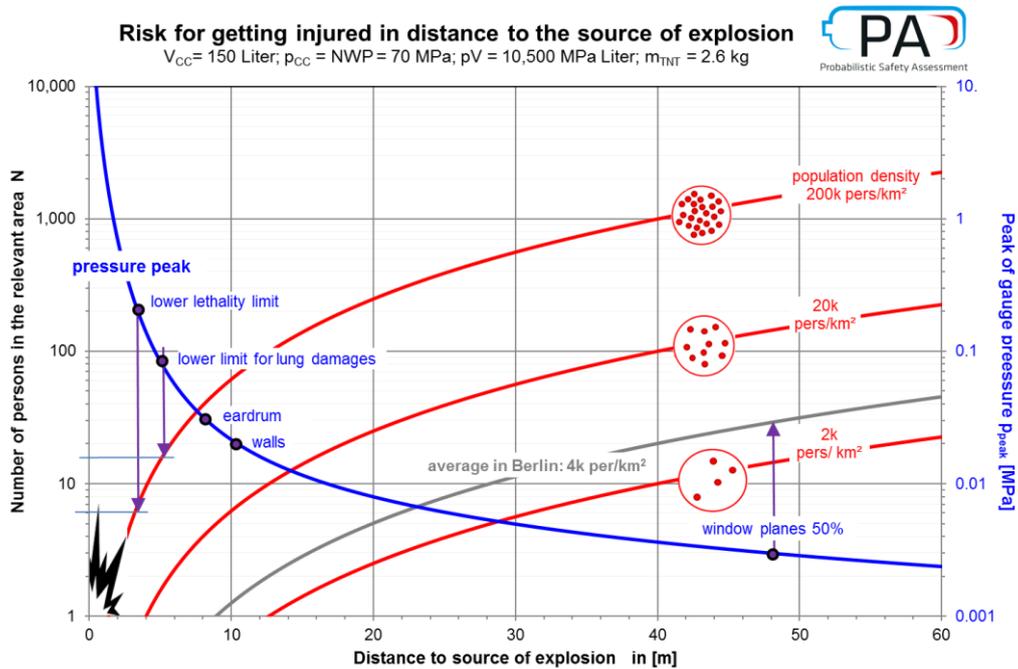


Figure 5: Shock wave pressure peak (see [15])

A bursting of 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. Based on this, it is possible to determine how many casualties there will be for a given population density [16]. 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.

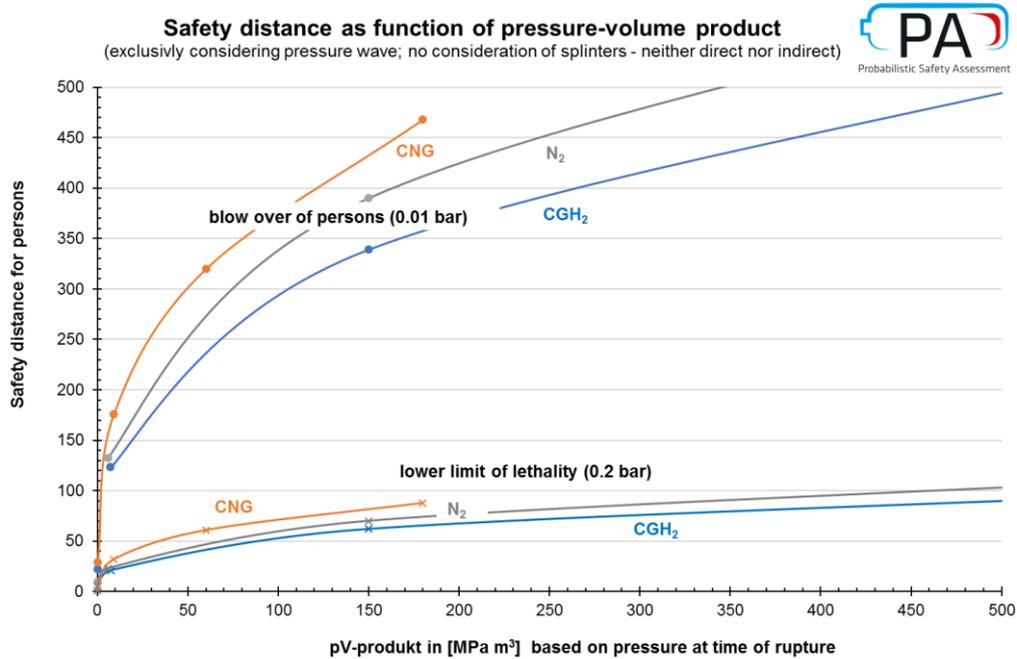


Figure 6: pV-product vs safety distance for different gases

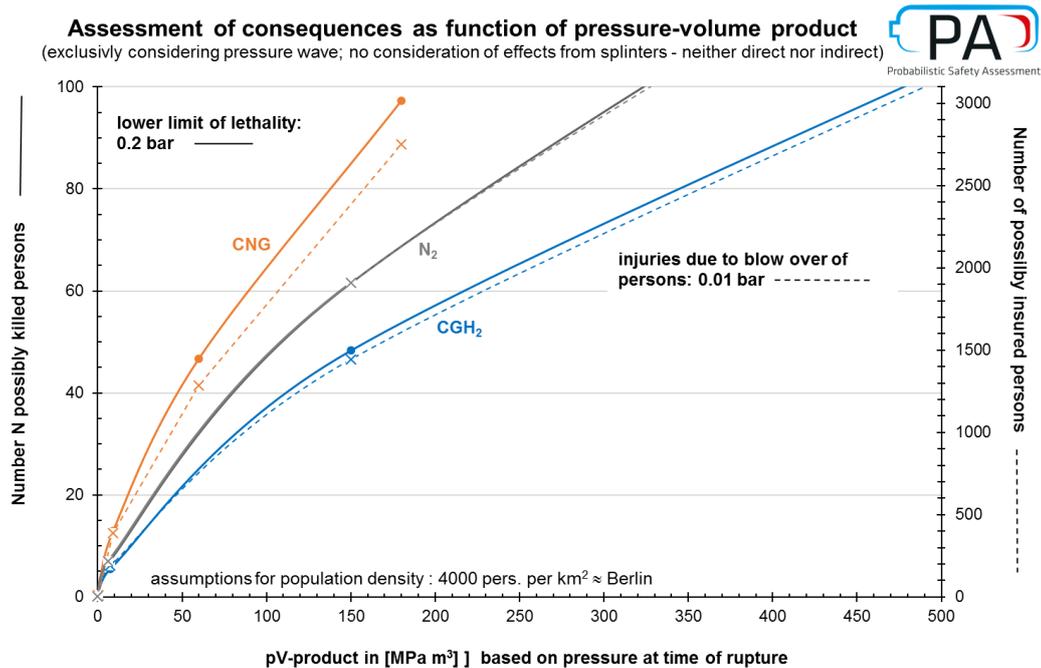


Figure 7: pV-product vs casualty count for different gases

Fig. 6 shows that a pressure wave caused by a rupture of a pressure vessel losing its energy and with the distance to the 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 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 from different pressure levels. Nevertheless, for nitrogen and hydrogen, they behave similar when correlated by a factor. This is a reliable hint that the pV-product is a useful description of consequences. Thus, based on this data, it is possible to determine the consequence for given cylinder designs. Fig. 7 also shows the positioning of CNG (compressed natural gas), which has by far the worst consequences caused by 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 litres may lead to a consequence of 40 fatalities; only because of the blast wave. The same line in the upper part of Fig. 8 shows the accepted FR per life time in accordance with the proposed acceptance rate introduced in Fig. 4. For this example, this result to an interaction of (N = 40; FR = 3 · 10⁻⁸) for pV-product of 100,000 MPa litres.

This dot (N = 40; FR = 3 · 10⁻⁸) presented in Fig. 8 cannot be allocated in Fig. 2. There, the lower line crosses at N = 40 a value for the frequency of failure per year of F = 2 · 10⁻⁹ is presented, which is the factor 1/15 lower. 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 20 years or more, a factor of 20 must be used in the comparison of both figures. Thus, without consideration of splinters BAM's approach stays much more conservative for the transport of hydrogen as the relevant F-N-curve for stationary plants in Fig. 3.

But beside the risk control there is an additional aspect resulting from the consequence, despite the relevant acceptable risk.

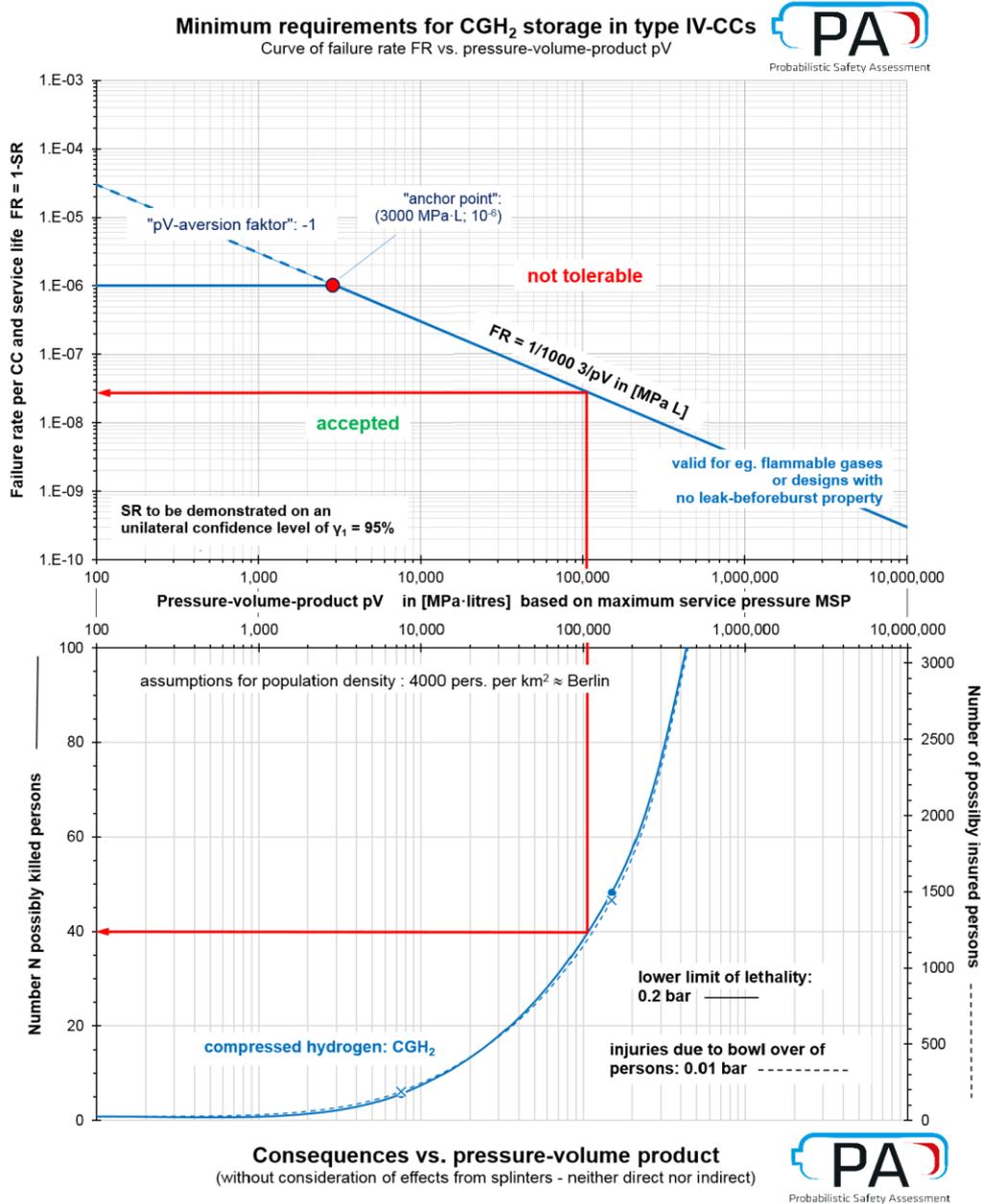


Figure 8: The combined usage of an F-pV-diagram with an FR-pV-diagram; cp. Fig. 5.9 in [15]

4. SPECIAL ASPECTS OF EXTREMELY HIGH CONSEQUENCES

On the other hand, the "KALKAR ruling" of the German supreme court (Bundesverfassungsgericht) [17] with reference to Article 2 (2) of the German Basic Law states that a special precautionary responsibility arises from a consequence of a possible damage event. In the case of special consequences, for example, 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, 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 solely area of competence of transport regulations.

With reference to consequence-probability diagrams (F-N-curves) accepted in broad areas of Europe, a catastrophe is said to have occurred in the event of a death toll of 45 or more [15]. 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 Swizz “Störfallverordnung StfV” (hazardous incident ordinance) [12] is presented in Fig. 9. It shows a critical value of 45 fatalities at which the consequence enters the area of a catastrophe.

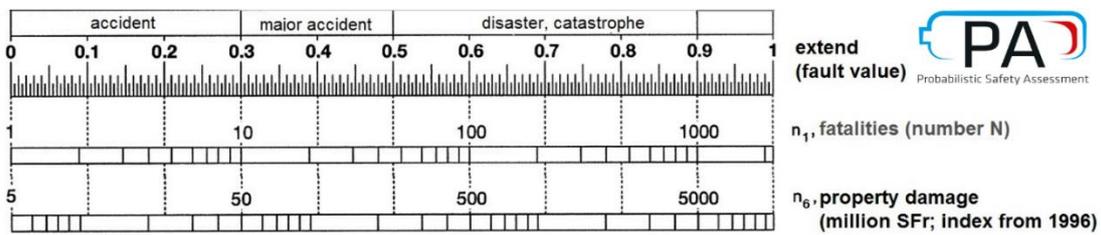


Figure 9: Source: RICHTLINIEN (1996) Beurteilungskriterien I zur Störfallverordnung StfV. Bundesamt für Umwelt BAFU, Bern [12]; translated from German

Such a catastrophic extent of damage 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 litres).

In view of the currently increasing size of the transport units for hydrogen (and natural gas) and the international efforts to change the current definitions of transport containments for gases to larger volumes, the consideration of the pressure-volume-product of pressure vessels in regulations for land transport takes on a new meaning.

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 as 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.

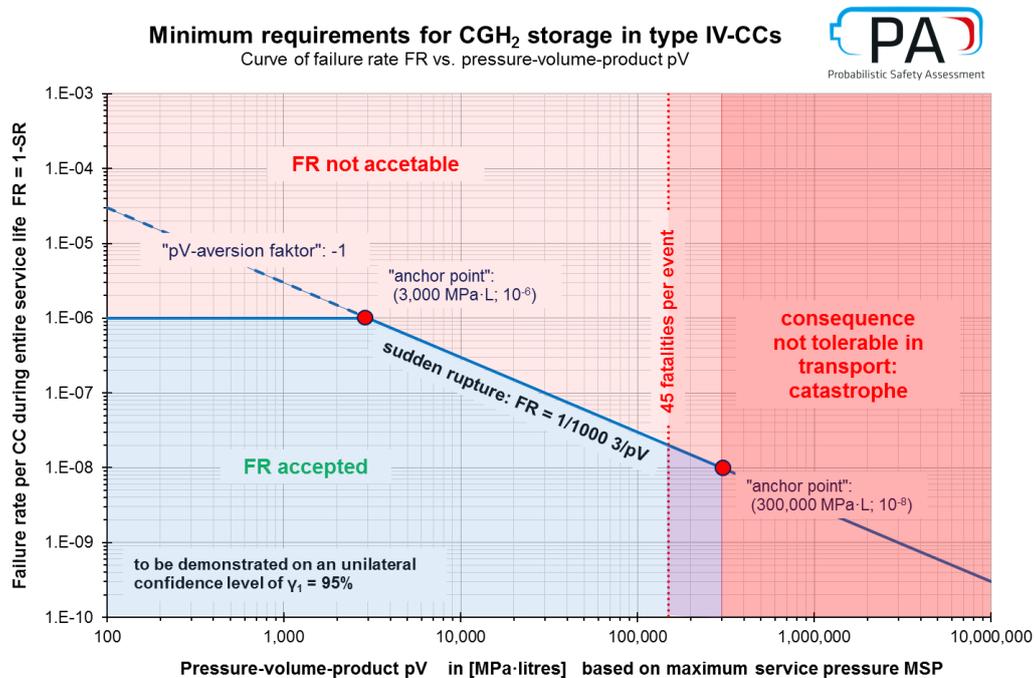


Figure 10: FR-pV-diagram for the risk control of gas transport

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 neither dangerous goods regulations nor vehicle approvals can provide a basis for adequate measures, risk management for mobile units is only controllable and acceptable up to a certain level of consequence.

5. A DEVELOPED VIEW ON RISK VALUES

The approach shown above for the consideration of risk limits was developed for stationary plants and used for these. It is also based on flanking location-based measures for surveillance and in emergency plans, which in this form are not applicable for mobile units of comparable consequence capability, as otherwise the basic idea of mobility would be taken ad absurdum by operating massive route restrictions as normal case.

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, for example. 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, comes to its limits if transport routes defined nationally without alternatives are not compatible with the transition points of 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, which means a very little part of whole transport volume and a limited number of routes. Organisation of high transport volume and far distance transports is hardly possible with such approaches.

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, 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 focussing on risk control the essential point must also not be forgotten: If you look 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. In opposite to that, transport vehicles on rail road (e.g. for chlorine gas) exists multiple; but the given rail route represents a linear location for these vehicles. If one compares 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 HTVs 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). While such an assessment would have to be arbitrary for chemical plants, a 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.

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

While in parallel the risk consists of the combination of the frequency of an event and the consequence of that event (cp. [6]):

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

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

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

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:

$$\text{Chance – risk analysis (transport): } \frac{\text{risk}}{\text{chance}} = \frac{n \cdot c}{m \cdot d} \quad (4)$$

6. EXAMPLARY ANALYSIS: TUBE TRAILER VS. BATTERIE VERHICLE

As an exemplary analysis, a comparison is demonstrated for a so-called tube trailer (Fig. 11 left) with seamless steel tubes built of several horizontally arranged tubes with a battery vehicle (Fig. 1 or Fig. 11 right), which is assembled from considerably more, smaller, but vertically arranged CPVs.

A general 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. Therefore, in opposite to the probability of failure, the consequence of a failure depends not on the number of individual elements. In this analysis 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 [13,18,19]: The used CPV is a legally called “tube” with 2000 litres and 500 bar maximum service pressure, which means a pV-product of 100,000 MPa litres. The tube trailer is constructed from 16 CPVs.



Figure 11: Conventional steel-tube trailer (left) and battery vehicle with 200 CPVs for hydrogen (right)

According to Fig. 8 and Fig. 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 cylinders 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 in Fig. 10 from CH [12], the consequence of 40 deaths is comparable with an economic loss of 200 Mio SFr (Schweizer Franken; i.e. Swizz Franks), which equals 175 Mio EUR.

This can be used for deducing the risk in EUROs posed by the tube trailer (TT) as complete vehicle:

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

Assuming a gas density for compressed hydrogen of 28 kg/m^3 at $T_{\max} = 65^\circ\text{C}$ and $\text{MSP} = 500 \text{ bar}$ (see [15]), a total mass of hydrogen per element (2000 litres) of 56 kg and 900 kg of hydrogen for the complete TT-vehicle is obtained. It is further assumed that an annual mileage of $50,000 \text{ km}$ will be achieved. This allows the advantage or chance of usage to be quantified as transport performance:

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

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

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

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):

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

If the same amount of gas is now transported with a battery vehicle (BV) with 200-litre CPVs, 160 elements (pV-product = $10\,000 \text{ MPa litre}$; 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, Fig. 8 and Fig. 10 is $3 \cdot 10^{-7}$. The assumed service life is again 25 years. 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 batterie vehicle (BV) analogously, one obtains:

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

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

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

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

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 batterie vehicle with 160 smaller tubes 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. Although the aspects of the increased probability of small leaks in the battery vehicle compared with the tube trailer, as well as the influence of accident situations that depend on the mileage, are 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. If you reduce the probability of failure as shown for the individual elements, in both cases you get vehicles that are exactly on the acceptance limit. The proofs and evaluations of extremely low failure probabilities of large and thus expensive CPVs tend to be less reliable than safety assessments of smaller CPVs. This

means not that safety level is lower but 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.

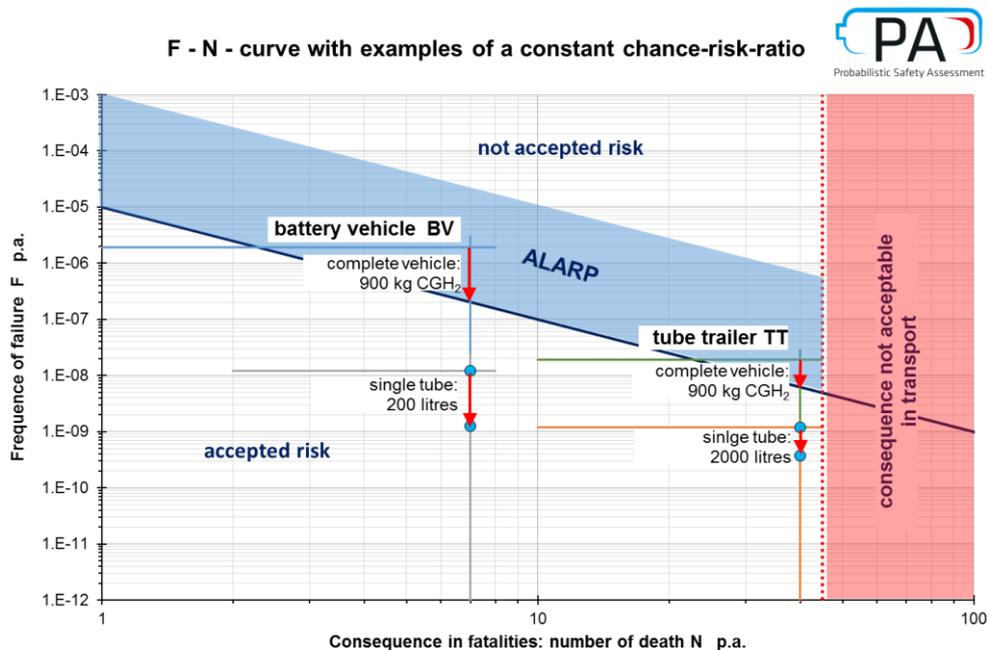


Figure 12: Risk-oriented correction of accepted failure rate for the CPV-elements based on the vehicles properties up to catastrophic consequences.

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”. Dependent from the individual safety aspect, there will be different optimal sizes, either objectively or just with respect to the demonstration of the safety level.

7. 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 is increasing. This is similarly valid for all gases used as energy carrier, 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 risk. This is even the case where a comparable risk can be assumed for each mounted pressure vessel.

The special conditions during the transition period of running up 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 [19]), which have high potential for consequence. At the same time, any approach comparable with the regulations for stationary plants is not sufficient 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 practically even important difference 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 five 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 social risk, 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 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.

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 not to jeopardise the acceptance of gases as energy carriers, in particular hydrogen.

LITERATURE

1. Weeda M. Hydrogen refuelling station and role of utilization rates: key messages and issues. Paris: IEA Hydrogen Roadmap Europa Workshop, IEA Headquarters: 2013. July 10
2. M. Azuma et al. Safety design of compressed hydrogen trailers with composite cylinders. *International journal of hydrogen energy* 39 (2014) 20420-20425.
3. Ke Sun, Xiangmin Pan, Zhiyong Li and Jianxin Ma. Risk analysis on mobile hydrogen refuelling stations in Shanghai. *International journal of hydrogen energy* 39(2014) 20411- 20419.
4. Norsk Hydro ASA, DNV. Risk acceptance criteria for hydrogen refueling stations. European Integrated Hydrogen Project (EIHP2); 2003.
5. Krishna Reddi, Amgad Elgowainy, Neha Rustagi and Erika Gupta. Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refuelling. *International Journal of hydrogen Energy* 43 (2018) 4428-4438.
6. Schulz-Forberg, B. (1997) „Yellow Paper“. Hamburg: Storck-Verlag; 1997.
7. Schulz-Forberg, B. (2016) „Das Qualitätsmerkmal Technische Sicherheit - Diskurs zwischen Risikovermeidung und Sicherheitsmanagement“. *Technische Sicherheit* Bd. 6 (2016) Nr. 5
8. European Directive for pressure equipment 2014/68/EU (PED)
9. EN ISO 14208 (2004): Transportable gas cylinders – Specification for welded pressure drums up to 1000 litres capacity for the transport of gases – Design and construction
10. ISO 11119-3 (2013): Gas cylinders – refillable composite gas cylinders and tubes Part 3: fully wrapped fibre reinforced composite gas cylinders and tubes up to 450L with non-load-sharing metallic or non-metallic liners. ISO: Geneva (CH)
11. Mair, G. W.: Hydrogen Onboard Storage – an Insertion of the Probabilistic Approach into Standards & Regulations? Presentation at the „International Conference on Hydrogen Safety ICHS“; Pisa: TU; Conference Proceedings 2005 on CD.

12. RICHTLINIEN (1996) Beurteilungskriterien I zur Störfallverordnung StFV. Bundesamt für Umwelt BAFU, Bern
13. Technical annexes (RID/ADR 2019) to the European agreements concerning the international carriage of dangerous goods.
14. BAM-GGR021 (2017): UN-Service Life Test Programme - Design Type Specific Determination of the Safe Service Life for Composite Pressure Receptacles on the basis of the Concept Additional Tests (CAT) <https://tes.bam.de/TES/Content/DE/Downloads/ggr-021.html>
15. G. W. Mair, Safety Assessment of Composite Cylinders for Gas Storage by Statistical Methods: Potential for Design Optimisation Beyond Limits of Current Regulations and Standards, Springer International Ltd. 2017.
16. Becker B, Mair GW (2015) Risiko und Sicherheitsniveau von Composite-Druckgefäßen, Technische Sicherheit 5 (11/12): 38–44; or in English: Risks and safety level of composite cylinders: Proceedings of WHEC 2016, Saragossa.
17. Bundesverfassungsgericht (German supreme court), 1978 BVerfGE 49, 89-Kalkar I
18. International Maritime Code for Dangerous Goods (IMDG Code), 2018 Edition (inc. Amendment 39-18)
19. United Nations (2019) UN Model Regulations, UN Recommendations on the transport of dangerous goods. Rev. 21, United Nations Publications, Geneva, New York