HYDROGEN ONBOARD STORAGE – AN INSERTION OF THE PROBABILISTIC APPROACH INTO STANDARDS & REGULATIONS?

Mair, G.W.
Federal Institute for Materials Research and Testing (BAM), 12200 Berlin, Germany

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ABSTRACT

The growing attention being paid by car manufacturers and the general public to hydrogen as a middle and long term energy carrier for automotive purpose is giving rise to lively discussions on the advantages and disadvantages of this technology – also with respect to safety. In this connection the focus is increasingly, and justifiably so, on the possibilities offered by a probabilistic approach to loads and component characteristics: a lower weight obliged with a higher safety level, basics for an open minded risk communication, the possibility of a provident risk management, the conservation of resources and a better and not misleading understanding of deterministic results. But in the case of adequate measures of standards or regulations completion there is a high potential of additional degrees of freedom for the designers obliged with a further increasing safety level.

For this purpose what follows deals briefly with the terminological basis and the aspects of acceptance control, conservation of resources, misinterpretation of deterministic results and the application of regulations/standards. This leads into the initial steps of standards improvement which can be taken with relatively simple means in the direction of comprehensively risk-oriented protection goal specifications. By this it's not focused on to provide to much technical details. It's focused on the context of different views on probabilistic risk assessment. As main result some aspects of the motivation and necessity for the currently running pre-normative research studies within the 6th frame-work program of the EU will be shown.

0. NOMENCLATURA

General abbreviations:

BAM	Federal Institute for Materials Research and Testing (BAM); partner within StorHy
CRP	Carbon fibre Reinforced Plastics
EU	European Union
PSE	Progress in Science and Engineering
RM	Risk Management
SA	State of the Art
SAST	State of the Art of Safety Technology
StorHy	Research project: Hydrogen Storage Systems for Automotive Application; compare with [8]
WER	Well-known Engineering Rules

Parameters:

C	consequence
F	distribution of frequency (failure or consequence)
F^*	frequency of an undesirable event
J	maximum value of the count variable j
N	number of running systems
P	probability of a failure (e. g. bursting) during use
R	risk
Z	reliability (probability of integrity after life time/use)
j	general count variable; safety coefficient
x	normalised deviation value of a GAUSS-distribution
x_a	normalised load amplitude
x_{AB}	distance measure in case of combination of two GAUSS-distributions called A and B;
y	general variable for the first dimension (e.g. of a GAUSS-distribution)
z	general variable for the second dimension (e. g. of a distribution)

σ_m average value of load or strength
σ_s standard deviation of load or strength

1. INTRODUCTION

The use of gas as a fuel in motor vehicles – be it liquefied gas, natural gas or hydrogen - is always accompanied by an intense discussion on its potential hazards. The feeling of trepidation which sometimes alarms a potential car buyer before he gets into gas-powered vehicles – at present largely natural gas (CNG) and in future certainly hydrogen – is mostly diffuse, indeterminate and hardly tangible. The fear of the "worst case", gas cylinders bursting, is sometimes compared in the press with the fear of nuclear radiation, for which humans also have no perceptual sense. In both cases there is no everyday experience which enables to human mind specifically to weigh the danger of the technology against the personal or social benefit it offers.

This often leads to a discussion dominated by prejudice, one in which every effort is made to compare the risks of natural gas and hydrogen with those emanating from petrol and diesel vehicles. In view of the great differences in terms of substance properties and, in particular, the methods of storage, it is hardly possible to make a direct comparison. For example, the density of liquid hydrogen is, at 70.8 kg/m³, only about 1/10 that of petrol, even at the boiling point of -253°C. This is also significant for the differences between the systems.
The formation of puddles of petrol that runs out of thin-walled fuel tanks also cannot be compared with the behaviour of escaping gas or even a bursting fuel gas storage cylinder.
With this in mind and in view of the ever shorter product and development cycles, both facets of risk study, namely a prospective probabilistic study of failure sequences on the one hand and accident statistics/maintenance statistics with the additional aspect of consequence on the other, are becoming increasingly attractive. With these forms of study, which are too rarely combined as yet because of their differing approaches, it is becoming possible to describe protection and effect goals which ensure that the hazard for a driver or an uninvolved third party from fuel gas technology is in no way greater than that from conventional fuels. This is also possible in terms of estimating the consequences of the technology.

Experience shows that, because of the novel nature of the technology, the very rare notable incidents with gas-fuelled vehicles have a greater impact and so remain longer in the public memory. But with pioneering technological applications which may be inevitable in the future, such as the use of hydrogen as a mobile energy source, it is particularly important not to jeopardize frivolously the acceptance of the new application by unbalanced or ineffective protective measures. To avoid this, many developers of tomorrow's hydrogen technology have already acknowledged that a probabilistic risk approach is helpful in keeping safety levels up, in conserving resources and hence in sustaining a high level of acceptance. The most important aspects will be highlighted here briefly in general form:

- **The probabilistic - a tool for the assessment of risk**
  The need for risk communication
  The notion of risk
  The probabilistic basic of deterministics
  Risk and system reliability
- **The probabilistic - three good arguments in favour**
  Conservation of resources through system study
  Example: “Safety” against bursting
  State of the art - freedom of developers
- **The probabilistic – first steps into the regulation ?**

2. THE PROBABILISTIC – A TOOL FOR THE ASSESSMENT OF RISK

2.1 NEED FOR RISK COMMUNICATION

The concept of risk is based on the endeavour to estimate hazards and to consider them together with the chance that taking a risk will bring. In connection with the discussion of risk, for example, a state of hazard is referred to when the risk exceeds a certain value, the limit risk. On the other hand one refers to safety if this risk is smaller than the limit risk. The limit risk may be specified by the legislator, but it is mostly the general acceptance of a historically developing risk which has crystallized parallel to a technical development. As new technical developments proceed at an ever increasing pace, the traditional, slow-acting regulation procedures often fail, being

nearly all "deterministic" in their orientation (the theory of determinism relates to the causal (pre-) determination of all events). It should be said at this point that a deterministic view can also be interpreted as a special case of probabilistics.
This physical special case of "determinism" is characterized by the fact that one is not working with a verified and quantified scatter of a characteristic, but with a "safety margin" in relation to an average of a characteristic which has mostly become established over decades.

With the means of empirical deterministics, however, it is also possible, thanks to the increasing internationalisation and consequent harmonization of the related "empirical approaches", that the national risk aspects which have worked hitherto of population density through to the level of general technological awareness are no longer considered with discrimination in the approval procedures. This means that the uncertainty is increasing on all levels concerning the hazard or risk emanating from a "foreign" technology. In order to diminish this uncertainty, it is essential to deal constructively and openly with it in the form of risk communication. But it is difficult to set out on this road in a comprehensively "secured" society, since it must initially be made clear and there must also be an instinctive awareness that safety does not mean that any hazard (risk) is prohibited. This is in no way possible: every technology involves risk and a residual risk is always inevitable. This has to be communicated first. By this the risk communication will help to decrease prejudice and help to choose e. g. the best storage concept for a certain use.

2.2 THE NOTION OF RISK

The notion of risk is based on an endeavour to estimate hazards. The notion of statistical risk R can also be described mathematically as a link:

$$R \equiv F^* \bullet C \qquad \text{Equation 1}$$

F^* stands for statistical frequency of an (undesirable) event and C for the statistical consequence from this event. If one approaches the same objective from the point of view of component probabilistics, one must work with the number of systems N, the failure probability P on the basis of the frequency distribution F_V and the consequence which is subject to a frequency distribution F_K.

$$P(y) = \int_{-\infty}^{y} F_V(y_1, y_2, y_3, y_4, y_5, \ldots)\, dy \qquad \text{Equation 2}$$

$$C(z) = \int_{-\infty}^{x} F_K(z_1, z_2, z_3, z_4, z_5, \ldots)\, dz \qquad \text{Equation 3}$$

The risk R can thus already be described prior to the statistical surveys from the company as a linking of two independent, multidimensional functions for a technical system and can be forecast as an approximation.

$$R(y,z) = N_{Systems} \cdot [P(y) \bullet C(z)]_{System} \approx F^* \bullet C \qquad \text{Equation 4}$$

This equation must be interpreted with the knowledge

1. that the consequence C represents a material and/or health damage;
2. that the reduction of a risk R, whether through probability or consequence, normally involves a monetary expense;
3. that the prohibition of damage to health and life would be equivalent de facto to a general prohibition of technology;
4. that the consideration of the consequences of risk in relation to a reduction in expense also ultimately represents a monetary view of health and life.

This sets for policy the difficult task of optimising limit risks economically according to an ethical evaluation. "Technology" itself can contribute, with its scientists as honest brokers, objective condition descriptions and the exposure of relationships. Comparisons with the risks of other technological fields can also help.

2.3. RISK AND SYSTEM RELIABILITY

The technical analysis of system reliabilities and the consequence statements that depend on a wide variety of failure scenarios for a system can only be formulated in the above equations through more extensive studies.

The consequence formulation in Equation 3 is based on different probability distributions for totality of the relationships affecting the consequence *C* and for all conceivable types of consequence, such as mechanical forces from the failure, material properties, geographical factors, population density, where relevant weather, etc.
The failure probability *P* (with system reliability *Z* as a complement) according to Equation 2 depends on the dimensioning of the technical system and the conditions of use, incl. maintenance, etc.

The risk formula can be evaluated technically if for each discrete event j (e.g. j = bursting of a StorHy-Element[*)] (e.g. cylinder) with N Elements in circulation) the relevant consequence C_j is determined from the total J of all possible events and is linked with the failure probability P_j of the respective event j, e.g.:

$$R_{j=Burst} = N_{Cylinder} \left(P_{j=Burst} \bullet C_{j=Burst}\right) \qquad \text{Equation 5}$$

The risk R is then, in simplified form, the sum of the individual event:

$$R = N\sum_{j=1}^{J} R_j = N\sum_{j=1}^{J} P_j \bullet C_j \qquad \text{Equation 6}$$

According to the relationship between risk control and achieved risk reduction as mentioned above, the consequence *C* is basically measurable in financial terms. With an occurrence probability *P* related to a time span, one obtains for a risk *R* monetary expenditure per period (e.g. [€/a]). The complement to "risk", the "chance", can also be rated as an achievable monetary gain over time in this economic context.

The example of a StorHy-Element[*)] in a motor vehicle can be taken here as an example of the consideration of system reliability and to illustrate various approaches to risk control.
The risk under examination for a system in operation comprises various individual risks. In this example these may be: leak due to liner fatigue, bursting due to excess pressure during fuelling, escape of gas due to the incorrect triggering of a pressure relieve device, hydrogen release due to underfiring after collision with a petrol-driven vehicle that catches fire etc. The level of the risk of all systems in operation is then, according to Equation 6, proportional to the number of systems in operation *N*.

As **Figure 1** shows, the point in time at which risk-control measures are taken (risk management RM) plays a major role with regard to the success of the controlling measures taken in the introduction of a new technology.

- If no counteracting measures are taken at all - which is a more academicals scenario - in the case of risks exceeding the acceptance limit, the market for a product will disappear. The technology counts as "burnt out". But this self-regulation often comes too late and mostly in a form which is neither socially nor economically acceptable.

- If the necessary measures are taken too late, it is not possible to prevent an overshoot with at least temporarily unacceptable risks. The acceptance of a product will be enduringly impaired.

Both scenarios should also be avoided with a view to the fuel gas technology – whether natural gas or hydrogen. It is in the interest of all those involved in fuel gas technology, whether the authorities, the vehicle manufacturer or the gas supplier, that the level acceptance be kept as high as possible or brought up to the highest level. For this reason two other scenarios should be considered as a matter of priority:

- The safety endeavours are maximized. This creates economic hurdles for the technology, which will mostly result in a lower acceptance from an economic point of view, due to the very expensive end products and rigorous conditions imposed with respect to operation.

[*)] StorHy-Element means an onboard storage containment of Hydrogen, used as fuel for automotive application; These can be a cylinder/tube or its bundles, a closed cryogenic receptacle or even a containment for solid storage.

- Ideally the early and predictive use of risk-controlling measures will lead to a controlled approach to the so-called limit of insignificance, which is located below the acceptance limit actually attainable. In this area the technology of, for example, the hydrogen vehicle is not negatively conspicuous on a sustained basis, and so question of safety do not impair attractiveness.

The questions therefore remains of what can be done in terms of predictive risk management in the interest of all to control immediately and enduringly the gas storage systems, with their relatively major consequences, as the central factors in the safety of the gas-driven vehicle.

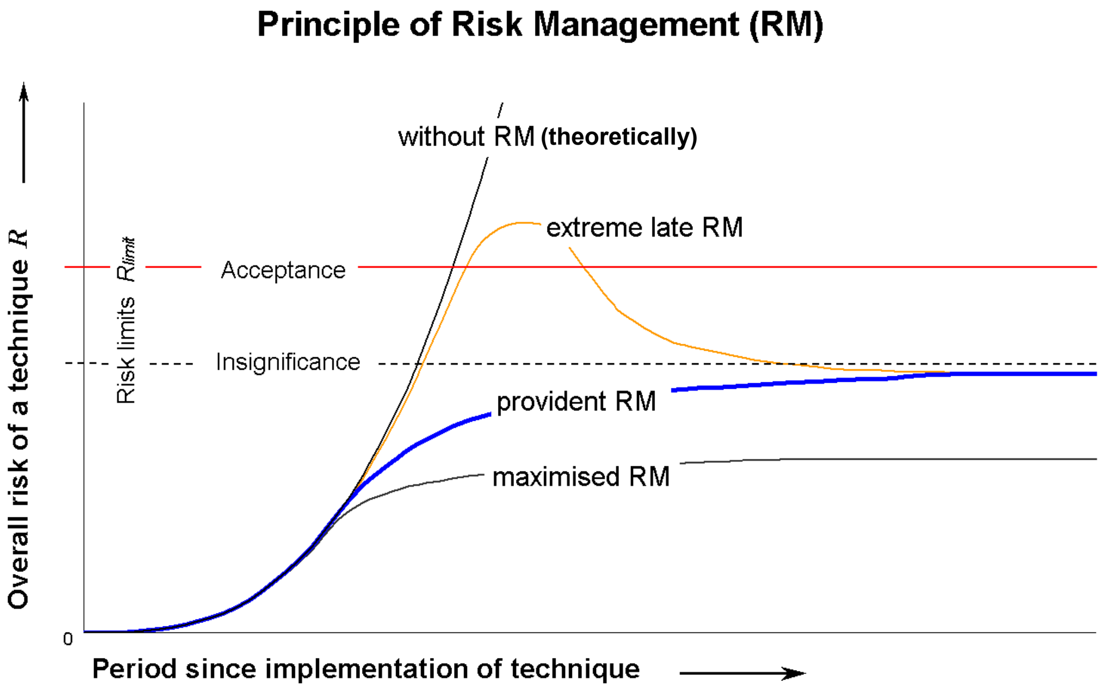

Figure 1 Diagram to illustrate the approach and effect of risk management

2.4 THE PROBABILISTIC BASIS OF DETERMINISTICS

At this point an explanation has to be given how a rigid deterministic specification of a safety coefficient looks from a probabilistic point of view.
The safety factor j is defined as the ratio of durability to load. Whether determined empirically or probabilistically, the safety factor has the function of guaranteeing the reliability of a design with the engineer's knowledge of the scattered nature of load (load assumptions) and durability (strength). The safety factor therefore rises with the demand for greater reliability. The same applies when the scatters of one or both base quantities for the safety factor, load and durability, become greater. If, on the other hand, the scatter ranges become smaller on account, for example, of the improved quality of production (greater conformity of products with the type), the safety coefficient can be kept smaller without any loss of reliability. The standard deviation of a distribution in relation to the mean is called the scatter or scatter factor c here. The distance X_{AB} is also used as a manageable quantity for the "overlap" of two distributions: It can be determined from the scatter ranges and the interval of the mean values [1]. This relationship is reproduced in the complex **Figure 2**. It is clear here that the occurrence probability V_{AB} of an event becomes smaller the greater the distance (amount) of the distributions.

If one determines a necessary safety factor empirically, it can be assumed that one is not working directly via mean values and scatter ranges, but using the results of verification tests. Normally these tests are so designed that no failure rate is permissible and the actual strength values are not registered. Something similar applies with regard to loads in which, for example, the "wind/wave of the century" etc. is used, but not the "wind of the millennium", without having at one's disposal a data catalogue covering many centuries. This means, for example, that one is working empirically, consciously or unconsciously, with reliabilities in terms of survival probability or reliability (Z=1-V_{AB}) of 90% or 99% in order to estimate the safety factor j for whole areas of technology via these empirical values.

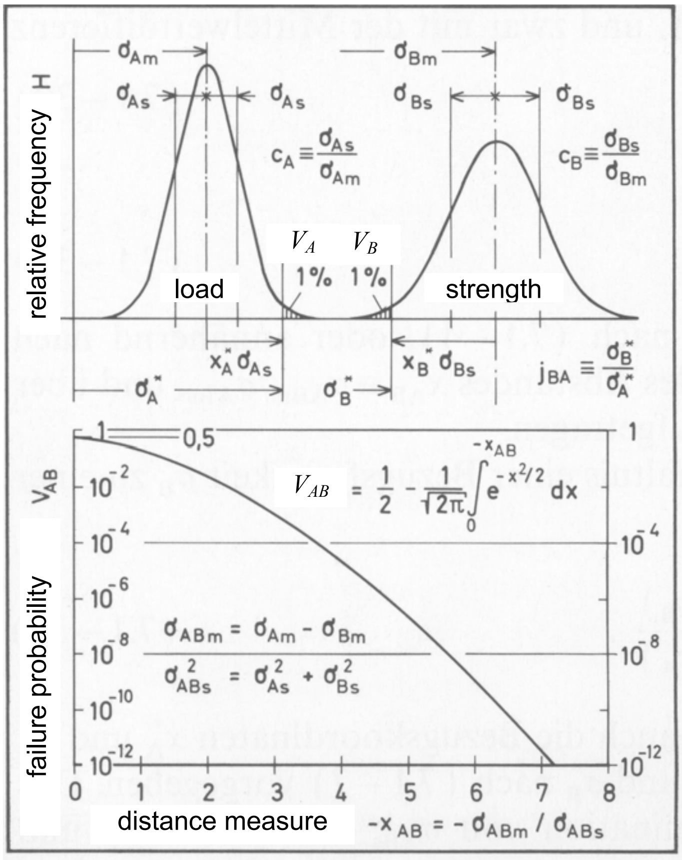

Figure 2 Influence of the scatter range or distance measure x_{AB} on the failure probability P_{AB}; from [1]

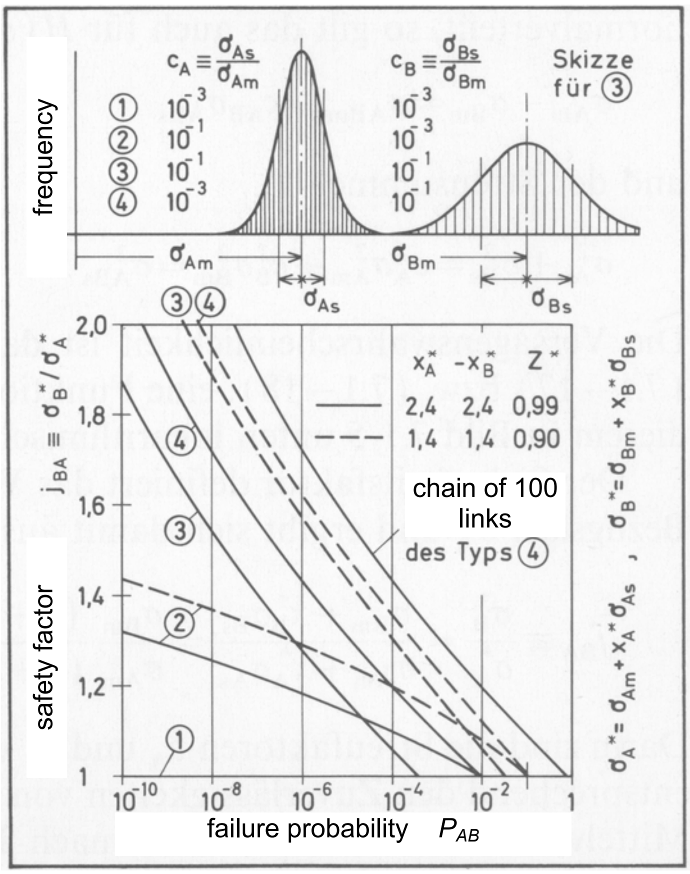

Figure 3 Relationship between the safety factor, scatter dimension and scatter range; from [1]

This is taken up in **Figure 3** and, in conjunction with various scatters, it creates the relationship between failure probability and safety factor. Further explanatory remarks on the principle of the Gaussian normal distribution and the example also shown of the "chain" can be studied in detail in [1].

Conversely the result obtained, however, is that a safety factor requires consideration of statistical values in order to achieve what is actually supposed to: to ensure with the requisite effort the necessary degree of safety in probabilistic terms without making use explicitly of the tool of probabilistics. The following is intended to illustrate that, in the case of complex structures, this depends on much more than the relationship just outlined.

3. THE PROBABILISTIC - THREE GOOD ARGUMENTS IN FAVOUR

Up to this it is shown that probabilistic is difficult, needs a good and substantial data base but offers some aspects of prospective risk analysis and of risk management for an optimised product acceptance on a high safety level.
But there are three good arguments in addition which make probabilistic tools very attractive for the future use in the development issues of fuel gas vehicle and especially their StorHy-Systems*).

3.1 CONSERVATION OF RESOURCES THROUGH SYSTEM STUDY

Quantitative risk approaches and probabilistic system studies can also help in making optimum use of the effort applied by a controlled adjustment of the solution to fit the requirements. By way of explanation, **Figure 4** outlines here the fundamental process according to which people mostly learn in the early phase of life how to optimize the construction of a tower from cubes (building blocks).

1. Dimensioning of the individual elements according to deterministic factors:
   Each component is designed in itself with the same certainties and is inserted in the system in a more or less accidental order without consideration of the interaction with other components.
   This means that the building blocks are stacked without any further, experience-prompted automatic process to form a tower in the order in which they are perceived and hence are available subjectively.

2. Dimensioning of the elements according to deterministic factors as a system: Each component is still designed in itself with the same safety and is inserted in a more or less accidental order in the system, but the components are positioned in the system taking account of the interactions. This means that the building blocks are still stacked in an arbitrary fashion, but the lessons learnt from initial experience have been put into practice, i.e. cubes must be placed precisely (with their centres of gravity) on top of one another to ensure that the tower is stable.

3. Conservation of resources by probabilistic optimisation of elements and the system as a whole: The components are no longer designed in themselves for the same safety. They are dimensioned according to their significance for overall reliability and inserted at a point in the system at which they can most safely be inserted with their characteristics, taking account of the interactions. This means that the building blocks are registered systematically as available resources. At the same time care is taken to ensure that they are graded according to the size of the standing area to be stacked into a tower. It is also taken for granted that the centres of gravity should be above one another.

This gives an outline not only of how a tower can be constructed to the greatest possible height using children's building blocks, but also of how the "probabilistic study" can help conserve resources.

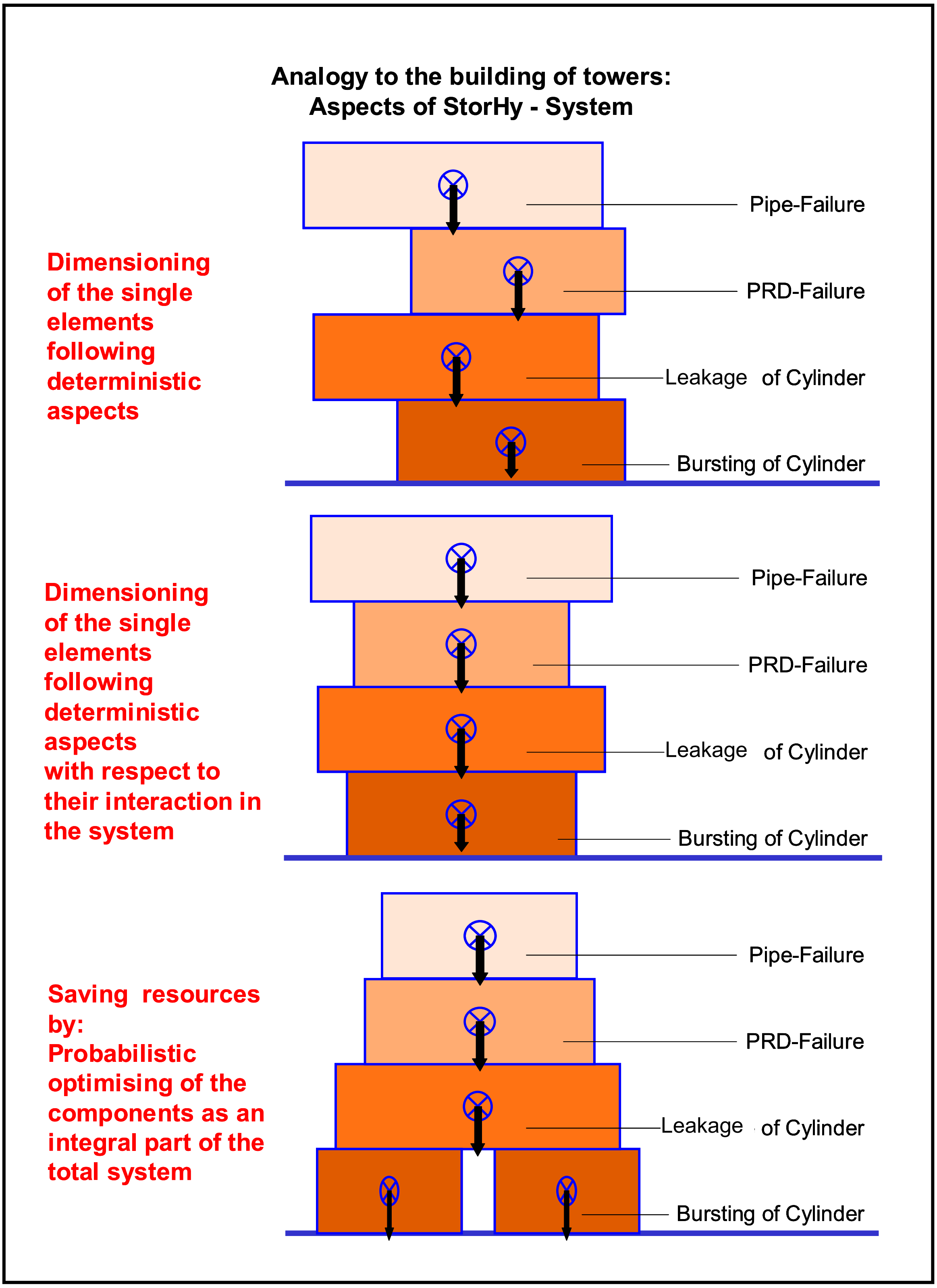

Figure 4 Optimum use of resources taking the example of a tower of wooden building blocks

3.2 EXAMPLE: "SAFETY" AGAINST BURSTING

The hypothesis to be proven is that a classic coefficient of safety may forfeit its significance as a criterion for safety in the sense of a risk protection goal when transferred to new systems, especially if they are statically indeterminate.

As is shown in [2] and [3] taking the example of circumferentially wrapped fuel gas cylinders, the probabilistic optimisation is based on the most detailed possible model of failure sequences. A clear distinction must be made here in particular between primary and secondary events, which may have differing causes on the different failure paths and their interaction must be examined. As is shown in **Figure 5**, such a model soon becomes complex even for the simplest components and without a detailed description. It can be studied in detail in [2] or [3]. The objective aimed at, which is taken as the basis for the illustrative sequence chart, is failure-safety through partial redundancy (fail-safe design) in the form of a primarily expected internal pressure relieving leak to prevent bursting with a high degree of reliability.

The example selected must be specified more concretely as a type II cylinder of steel with carbon fibre for use on the roof of a single-decker local bus. The load determined for the specific use and the lifetime laid down for the vessels is 5000 load cycles in 15 years. The load universe is described according to [4] and [5] as a distribution function H_S over the normalised load amplitude x_a and in its form by the exponent 3. With the natural logarithm of ln(5000) ≈ 8.52 the following applies:

$$H_S = 5000 \cdot \exp(-8{,}52 \cdot x_a^3) \qquad \text{Equation 7}$$

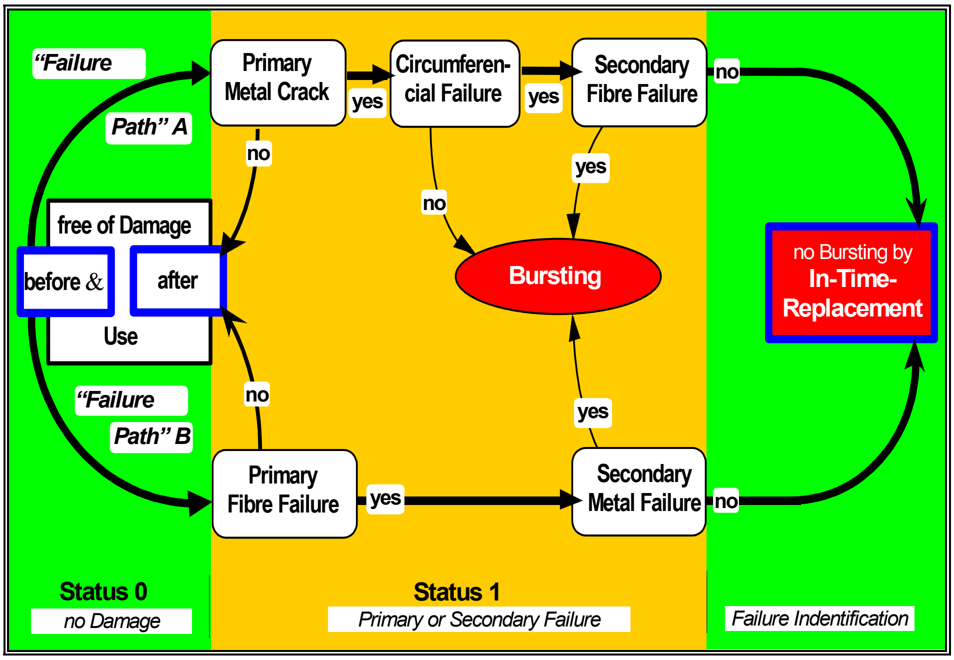

Figure 5 Two-stage nature of the failure sequences of circumferentially reinforced composite cylinders (see [3]; extensively simplified)

As protection goal the upper limit of the failure probability "burst" under the parameters being considered of $V_{Burst} \leq 10^{-2}$ is taken initially for the example chosen here. The second-rank protection goal is the specification that a maximum of 1% all fuel gas cylinders may develop a leak by the end of the lifetime ($V_{crack\ growing} \leq 10^{-2}$).
If one now evaluates the results from [2] which are explained shortly in [3] and satisfy all these requirements - albeit for slightly varying parameters (parameter: impact influence) - according to the static safety coefficient obtained and the weight required for the structure, one arrives at a result which, at first glance, is clear, but misleading. It is shown in **Figure 6.** although all optimisation results satisfy the protection goals in the form of restrictions, the different optimisation results exhibit very different static safety coefficients.

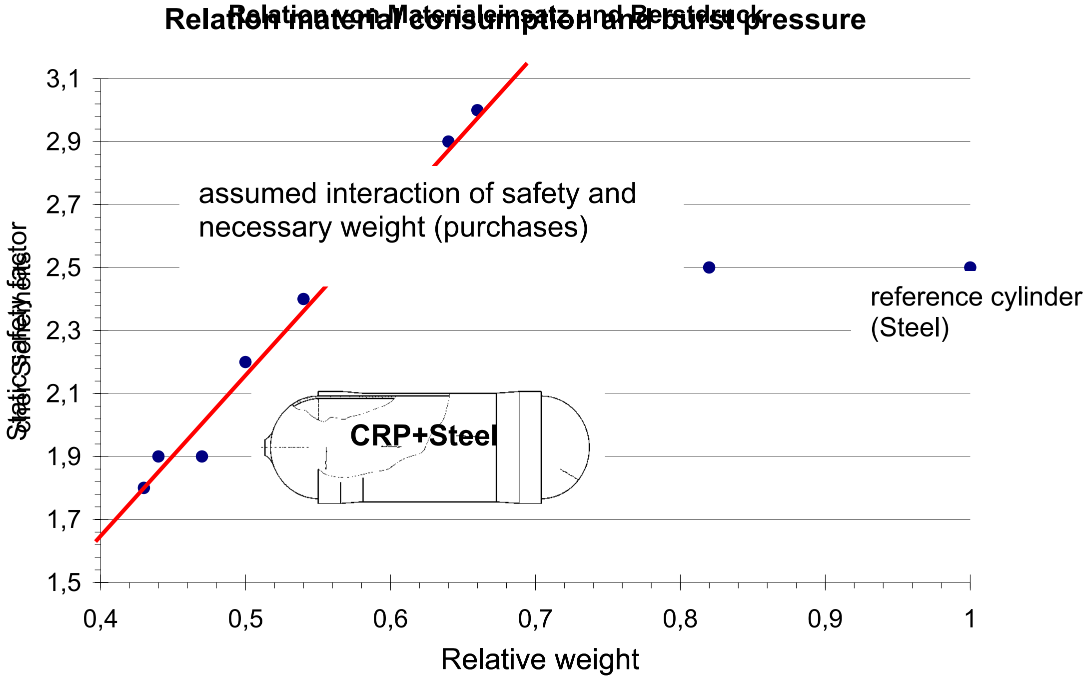

Figure 6 Interaction of weight and safety coefficient *j* for the circumferentially wrapped steel cylinder; all optimisation results from [2] or [3] evaluated satisfy the requirement of $P_{Burst} \leq 10^{-6}$ and $P_{crack\ growing} \leq 10^{-2}$.

The relatively light-weight hybrid cylinders shown in the left half of the picture reflect a supposedly systematic relationship between deterministic safety coefficient and weight (in relation to the reference steel body). But if one considers the significance of the static safety coefficient in the context of the state of safety in terms of the risk study it can be said that all points in the chart stand for the same risk (see **Figure 7**).

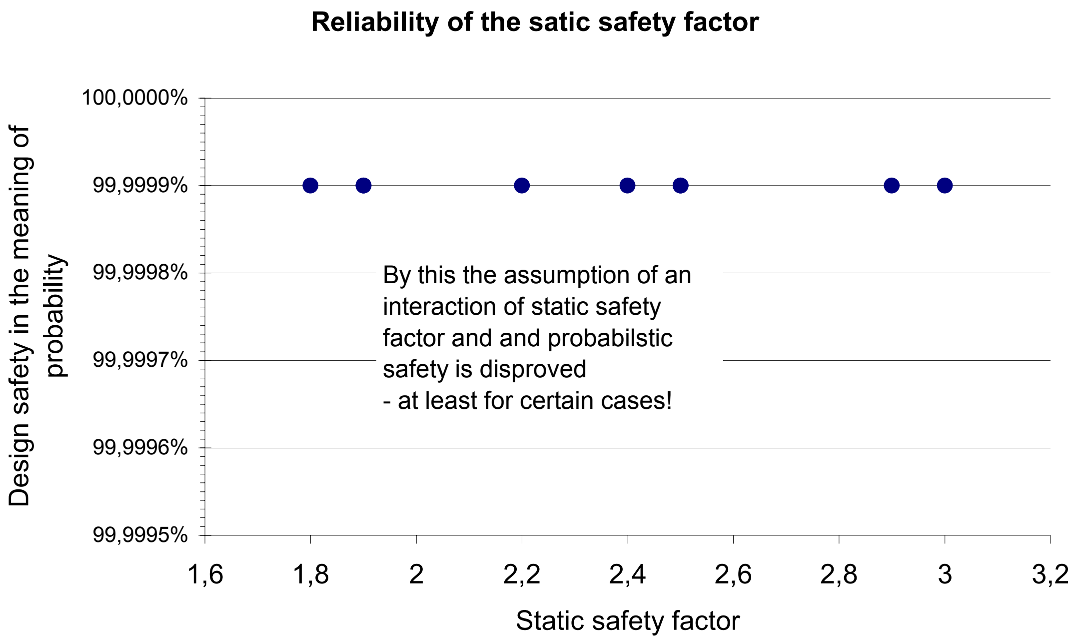

Figure 7 Relationship between safety factor *j* and reliability *Z* for circumferentially wrapped steel cylinders; all optimisation results from [2] or [3] evaluated satisfy the requirement $P_{Burst} \leq 10^{-6}$ and $P_{crack\ growing} \leq 10^{-2}$.

Every point represents an optimisation result with the bursting probability of $1*10^{-6}$ and thus satisfies the same risk-based protection goal with only minor variations in the operating conditions. Since the optimisation results are based on equal gas pressure and equal volume, it may also be assumed for them that the consequences will be comparable in the case of a burst. All points therefore reflect the same acceptable risk and hence the same safety. The initial impression of a relationship between safety and weight is therefore shown to be misleading in this context. So the Figure 7 is just another representation of the results of the results which are shown in Figure 6 already.

This therefore shows that the static safety coefficients, which can be described as classic for deterministics, are neither a qualitatively nor quantitatively suitable measure for safety, even in the case of relatively simple, statically indeterminate components such as composite gas cylinders. On the other hand, probabilistic study, which is certainly considerably more laborious at least in the initial phase, yields better and clearer results - in the synthesis and in the analysis. Once is fully justified here in pointing to the development in aerospace technology and its successful pioneering role to date.

3.3 STATE OF THE ART – FREEDOM OF DEVELOPERS

The manufacture and distribution of products with a relatively high risk potential, such as electrical machines, explosives or hazardous goods enclosures, are not matters of individual discretion. The requirements for electrical machines, for example, are subject to regulation, even if the manufacturer can in many cases confirm fulfilment of these regulations himself without the direct involvement of a neutral third party. In other statutory areas such as the transport of hazardous goods or the operation of motor vehicles, there is a general prohibition with a permission proviso. For example, a neutral body (a so-called independent third party) must be engaged when obtaining permission for hazardous goods packaging of cardboard in order to ensure safety by means of the tool of approval or, increasingly, certification. This is normally done with a view to the mostly chemical hazard potential of this packaging's content.
In addition, by the so-called "Kalkar judgement" of the German Federal Constitutional Court of 1978 (pleas see [6]) it was confirmed, that there are technology applications such as handling radioactive materials, which have to satisfy the state of the art (SA) in addition to fulfilling the regulations and standards and hence the "well-known engineering rules" (WER).

As is shown in **Figure 8**, there is on the time axis an intermittent, fundamental relationship between the two levels of "risk control". In addition to this the Figure also shows the state of the art of safety technology (SAST) and progress in science and engineering (PSE).

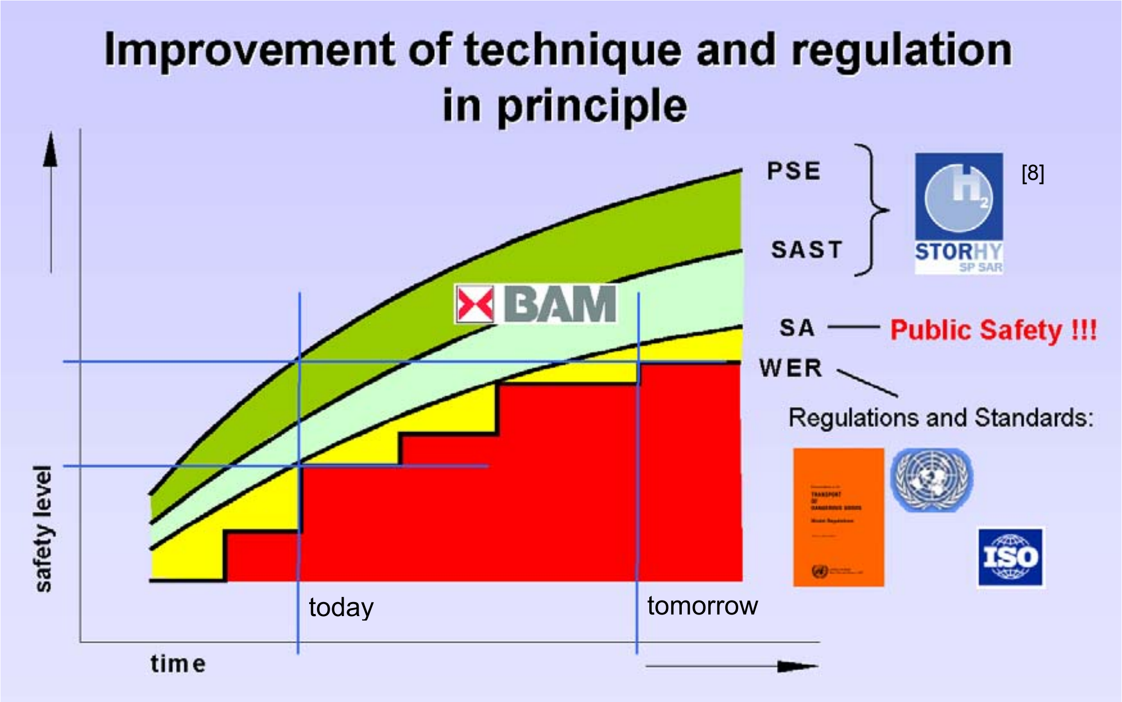

Figure 8. Interaction of the state of the art (SA) and the well known engineering rules (WER) [7].

The requirement that the SA be fulfilled also applies on account of the high consequential potential in principle for fuel gas technology – e.g. hydrogen-driven cars. Since the development of vehicle and storage technology is much more dynamic that a set of rules can be, the aim should be to find ways of making it possible to fulfil the rules dynamically without having to eliminate the detail of technical progress. The most far-reaching, but also most sophisticated approach here is that of probabilistics.

One can imagine that in the medium to long term it will no longer be common practice to verify a certain lifetime at a certain pressure on a defined number of test specimens. Rather it will be possible to formulate directly a protection goal in units relating to the weighing of economic opportunities/benefits. This could, for example, involve providing evidence that the risk of a vehicle does not exceed a certain monetary amount per year. As was explained earlier, health and even life must necessarily be measured in monetary units, at least by way of the financing of measures to be taken.
It is an open question whether such an approach will be practicable, but it would have considerable advantages for the designers. They would no longer have to optimise their products with a view to the requirements of design standards without being able to discuss in a short time whether the safety would even be reduced by this in an individual case. Such discussions normally require many years of successful participation in the relevant standardization committees.

4. THE PROBABILTIC - FIRST STEPS INTO THE REGULATION ?

The initial steps in the general direction of the statistical recording of component characteristics involve the slow, but targeted and continuous transition from verification tests with a yes/no decision to regulations and primarily design standards which also require that scatter ranges on the strength side be recorded quantitatively. This could be supplemented by complete system tests which will necessarily keep a deterministic yes/no approach.

In addition this quantitative-statistical component approach would also involve, of course, a more thorough determination of the actual loads and their scatter. This is particularly interesting if, for example, various filling procedures are in competition in hydrogen storage technology, signifying different pressure and temperature loads for the StorHy-Element*). It is not of primary importance here whether this filling procedure is used for hazardous goods transport, to drive a vehicle or in industrial components.

In the area of hydrogen storage the initial steps which would be appropriate in order to determine strength in quantitative terms could include not breaking off lifetime tests prematurely prior to fatigue failure and conducting them with respect to residual stresses at particularly critical temperature states. It also does not make much sense with such an approach to interrupt the damage process in the course of a test by changing the load (e.g. applying cyclic load under varying conditions with subsequent bursting). Rather the loads and conditions in strength tests should be designed so as to be uniform up to failure, even this means applying loads that do not arise in practice.

Examinations conducted in connection with probabilistic studies always have to focus on understanding the failure processes and drawing conclusions on reliability from loads which are as clearly separated as possible. This also applies if it is also necessary, in order to limit the time required, to obtain information from these tests on behaviour in operation with normally lower loads.

Other examples include verifying implemented fail-safe features or testing the behaviour under extreme situations without load relief devices etc. This list could be extended indefinitely and in greater detail. But at this point reference will be made to the results expected from a wide variety of research projects, especially in fuel gas technology (e.g. IP “StorHy”, see [8]).

5. SUMMARY AND OUTLOOK

To summarize the following can be stated:

- ✓ … it is necessary to develop a new assessment procedure in order to ensure a sound assessment of safety level and to guarantee the positive acceptance of gas-driven vehicles;
- ✓ … deterministic protection goal specifications and design procedures can only deliver what is required to a limited extent;

- ✓ … quantitative risk management including probabilistic optimisation is a proven means for doing this, possibly the only appropriate means;
- ✓ … probabilistic system optimisation generally offers new possibilities with respect to economic efficiency and the formulation of protection goals or public technical safety.

In order to ensure the safe storage of fuel gas and enhance the acceptance of Hydrogen vehicles as a whole then, the task is to develop usable tools of a quantitative risk analysis:

- which help to use technical measures and handling regulations where they have the greatest effect and are thus most efficient,
- which permit the inclusion of the spread of a technology and its place of use in the safety analysis,
- in order to maximize the acceptance of new technologies such as natural gas and hydrogen in the motor vehicle.

We are only now setting out on the road indicated here and described here as meaningful. This means that the major part of the journey therefore lies before us in all respects. The steps which must necessarily be taken, from the present point of views, are:

- ➢ initially a selectively partial, but continuous adaptation of regulations and especially standards to cover more the strengths properties actually present in a statistical manner;
- ➢ the increased formulation of detailed failure models/scenarios;
- ➢ a study of the consequences, incorporating the statistics available;
- ➢ an increased, statistically representative coverage of component behaviour, and not only in the case of major damage that has occurred;
- ➢ the inclusion of population density in the perspective-based consequence analysis;
- ➢ the setting up of a culture of risk communication with an open discussion of the risks accepted and those not accepted;
- ➢ the formulation of protection goals based on probabilistic risk studies.

For the sustainability aimed at in the acceptance of gas-driven vehicles, the introduction of Hydrogen technology will certainly not be get without probabilistic analysis and without the description of the relationships between operating load and product characteristics, and finally it will also require a risk study based on this.

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