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Hydrogen Applications in the Aircraft Sector

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Introduction

Due to its promising properties, hydrogen has become increasingly interesting for the aircraft industry. Nevertheless, its possible applications also require answers to the question of how to establish and demonstrate sufficient safety.

The paper is organized as follows: First, we start with a short overview over basic properties of hydrogen and ideas of using it within aircrafts.

After a review of basic risk and safety aspects we then discuss how risk strategies are implemented within the automotive sector where the development has progressed significantly during the last years.

In the main part we apply the general ideas to the problems of fire and cabin safety by demonstrating the junction of quantitative risk assessment methods with design methods and discussing implications of IEC 61508.

1. Basic properties of hydrogen and its application for aircrafts

Hydrogen is considered an alternative fuel for three reasons: It is lightweight, renewable and it is the most abundant element on the earth. The major advantage of hydrogen is that it stores approximately 2.8 times the energy per unit mass as gasoline, i.e. it supplies more energy per unit volume than gasoline, diesel, or kerosene. There are several ways to extract the energy contained in hydrogen: By combustion (internal combustion engines, ICEs, or turbine engines) or by converting it to electricity in a fuel cell. Research and development projects have demonstrated that using hydrogen is feasible today. Therefore, hydrogen also gets a very important status for aviation.

On the other hand, hydrogen shows a wide explosive range, coupled with very low ignition energy. Therefore, an accumulation of hydrogen in a poorly ventilated room can easily result in an explosion. Furthermore, the minimum ignition energy required to ignite a hydrogen mixture is 0.02 mJ, which is equal to the energy of a static electric discharge from the arcing of a spark. These properties force us to consider also safety aspects if handling hydrogen. Nevertheless one also should not forget that the diffusion coefficient for hydrogen is about 0.61 cm^3/sec, which means that hydrogen mixes with air faster than does gasoline or kerosene vapor. Hydrogen's low vapor density and high diffusion coefficient cause it to rise quickly, so that in the open, hydrogen mixes with air and disperses rapidly with no pooling on the ground – unlike petroleum-based fuels.

Currently, the usage of hydrogen for auxiliary power systems is of special interest for aircraft industry. Performance evaluations show two favorable fuel cell (FC) processes for aircraft applications, Proton Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC). FCs use gaseous hydrogen (GH_2) which may be provided by

- GH_2 in pressurized tanks,
- LH_2 in insulated tanks,
- reforming hydrocarbons.

Kerosene reforming is presently the preferred solution for aircrafts because only one fuel type (kerosene) is onboard, in addition with a 4 times higher density than LH_2. To produce hydrogen from kerosene, steam reforming, partial oxidation and autothermal reforming are considered as possible solutions. What about safety aspects?

In general, aircrafts must be engineered properly to minimize risks to the occupants, i.e. passengers and crewmembers. In commercial aircraft, safety is assured by first identifying hazards and then performing a fault hazard analysis. In this approach (see, e. g. Levenson [1], FAA [2], EASA [3]) the hazards are traced to the aircraft components with their respective failure modes. Each hazard is assigned a reliability target such that the aircraft as a whole will reach the FAA/EASA failure rate requirements [2], [3]. Then the components are designed and manufactured taking into account these allocated reliability rates. This again is assured by using a high degree of single element integrity, fail-safe-design (using redundancy and other design approaches to handle single or multiple component failure), and careful procedures where designs are modified to prevent previous causes of accidents.

This procedure has proven to be very successful in the past for several reasons: First, commercial aircraft designs do not change considerably over time. Learning from the past is therefore very effective. Secondly, commercial aircraft industry being very conservative in design approaches does usually not push the technology envelope. As soon as new technology has been introduced in the past, such e. g. fly-by-wire, increased accident rates have resulted on these high-tech-aircrafts and the mechanisms and causes have changed (e. g., pilots are making different types of errors). Another and third characteristic of commercial aircraft is that it is tightly regulated which again affects safety.

Can we adopt this strategy for the introduction of hydrogen? Take as example the production of hydrogen by a reformer. In this case experiences must be used which are obviously not available for aircrafts. Furthermore, there is no long-term experience (or no experience at all) with these systems and components in the transportation sector in general and even if they existed we did not know whether these experiences can be “translated” and applied to commercial aircraft industry. Finally, we have no generally applicable codes or standards available which could serve as guidelines to handle all these problems – we don’t even have such regulations in the automotive sector in spite of the fact that intensive efforts have been made by all big car-manufacturers in the last decades.

So the careful step-by-step approach characterized above is not possible in our case. Does this mean that we have to wait for an indefinite time until we make use of all the promising and positive properties of hydrogen?

We do not think so, on the contrast: In the following chapters we discuss an overall approach which includes the basic philosophy of risk management, the already existing safety concepts, tools and methodologies of commercial aircraft as published by FAA/EASA and also the existing experiences of handling hydrogen in other application fields. This approach should therefore bring about public acceptance as well as approval by authorities.

2. Basic Aspects of Risk and Safety

2.1 General Remarks and Definitions

Following a usual terminology risk can be defined as combination of the probability of occurrence of undesirable consequences and their severity [4]. Such undesirable consequences can be physical injury or damage to the health of people, damage to the environment or to property.

This combination is usually summarized in the symbolic equation

Risk = Likelihood · Undesirable consequences (1)

It is useful to distinguish between “risk” and “hazard”: Hazards exist as source with a potential to cause undesired effects to human, property and the environment (potential risk). The risk, on the contrary, includes the likelihood under which this source can be transferred into actual damage. With the use of adequate protective measures, risk can be reduced. Risk, therefore, depends not only on the hazard, but also on the protective measures taken against the hazard. These measures do not only include technical solutions, but also human intervention and risk management. The answer to the question “What would be the adequate protective measures so that the level of (actual) risk from a given hazard (potential risk) will be low enough (lower than a given threshold)?” is certainly one of the most important issues of risk analysis.

Following our symbolic equation shown above, we can derive the following equation for constant risk:

log(Likelihood) + log(Consequence) = const. (2)

So, in a double-logarithmic graph, we find that curves of constant risk are lines with slope –1:

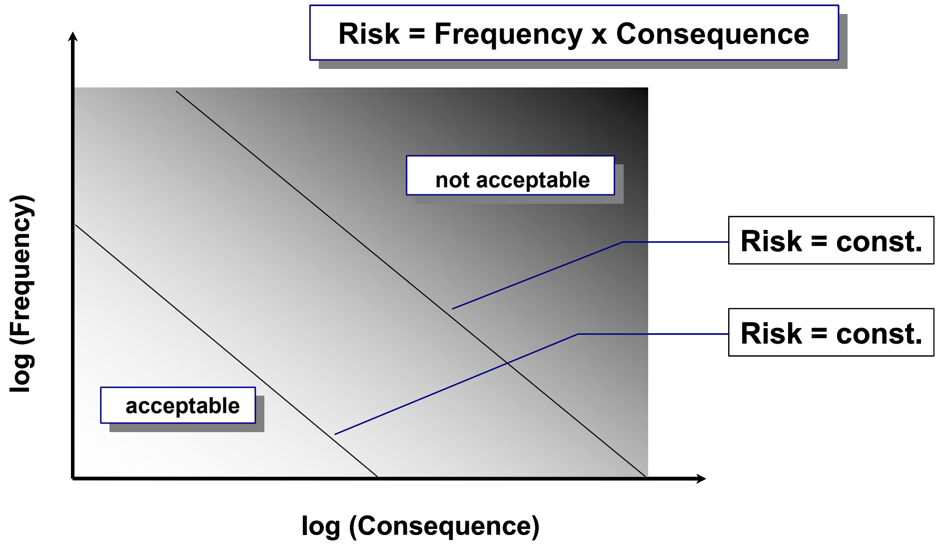


figure 1: General risk diagram

If we start in the lower left corner of the risk diagram and move to the upper right corner we are moving in the direction of increasing risk. So we are first in the “low risk region” or at “acceptable” risks and end with “high” or “unacceptable” risks. Of course, there is no clear border line between these regions – we have to define it (see below). Anyway, “safety” can now be characterized as “freedom from unacceptable risk” [4].

Without any protective measures, each hazardous state would immediately result in negative consequences. The resulting risk of the equipment considered (EUC in figure 2) would be usually too high compared to a given tolerable risk target.

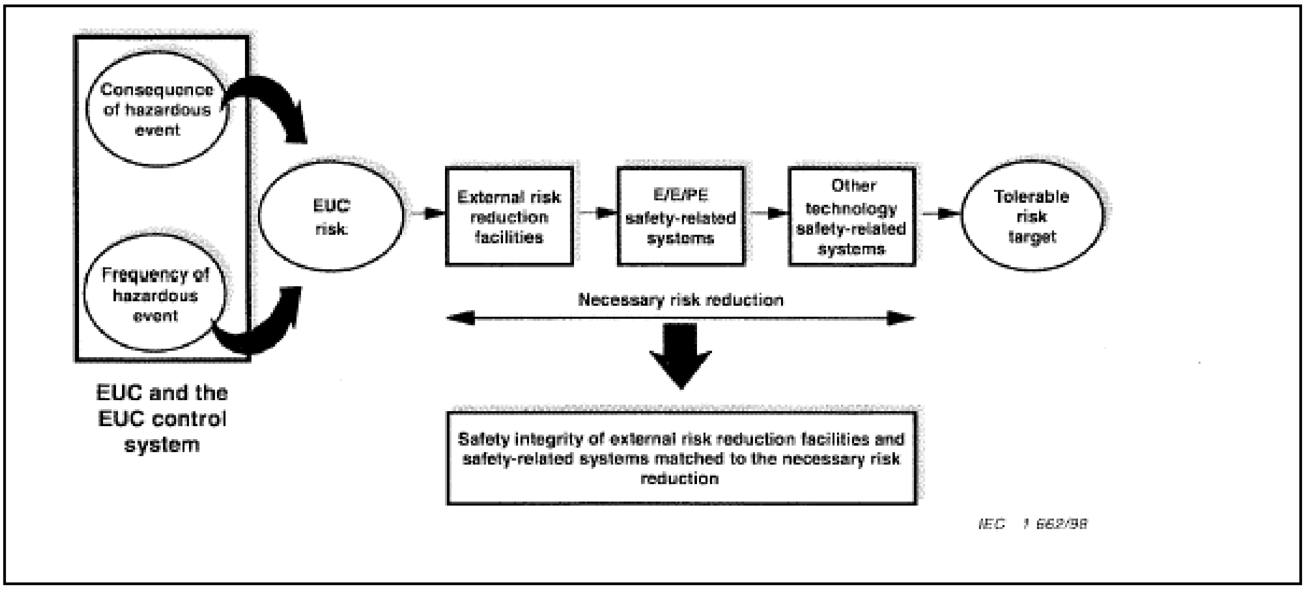


figure 2: Risk and Safety Integrity (from [4], part 5)

To achieve safety, the risk must be reduced by suitable functions (“safety functions”, [4]) which are intended to achieve or maintain a safe state for the system. Physically, these safety functions are realized by technical systems (e. g. electrical/electronic/programmable electronic (E/E/PE) systems). There is a certain (hopefully high) probability of a safety-related system satisfactorily performing the required safety functions under all stated conditions within a stated period of time. Following [4], this probability is called “safety integrity” in figure 2.

Several well established methods can be used for calculating the probability of dangerous failures of the system: Fault Tree Analysis (FTA), Reliability Block Diagrams (RBD), Markov Analysis, System Simulation using Monte Carlo Methods. The methods are described in detail in handbooks for the corresponding existing programs or in relevant textbooks for reliability engineering and shall not be discussed here again together with their advantages and drawbacks. In our context, it is important to note that the different methods have one thing in common: They describe quantitatively the failure modes and the effects of failures of the main components by a logical analysis of the functional dependencies between the components. Failure modes together with the component form the “basic elements” of the analysis, and corresponding failure rates or failure probabilities for these elements have to be fixed then. We need quantitative values for the rates or probabilities, or, to be more precise: The parameters are not fixed values, but continuously distributed random variables and the relevant distributions are characterized then by form-parameters, mean values, standard deviation etc. Thus one needs a function with several parameters just to describe one failure mode for one component. To derive such a function requires a broad operational experience with the component at comparable ambient and operational conditions.

Besides technical solutions, an overall risk analysis also takes into account other "barriers", e.g. rules, procedures and process knowledge of the operators or unplanned circumstances likely to avert or mitigate negative consequences (figure 3).

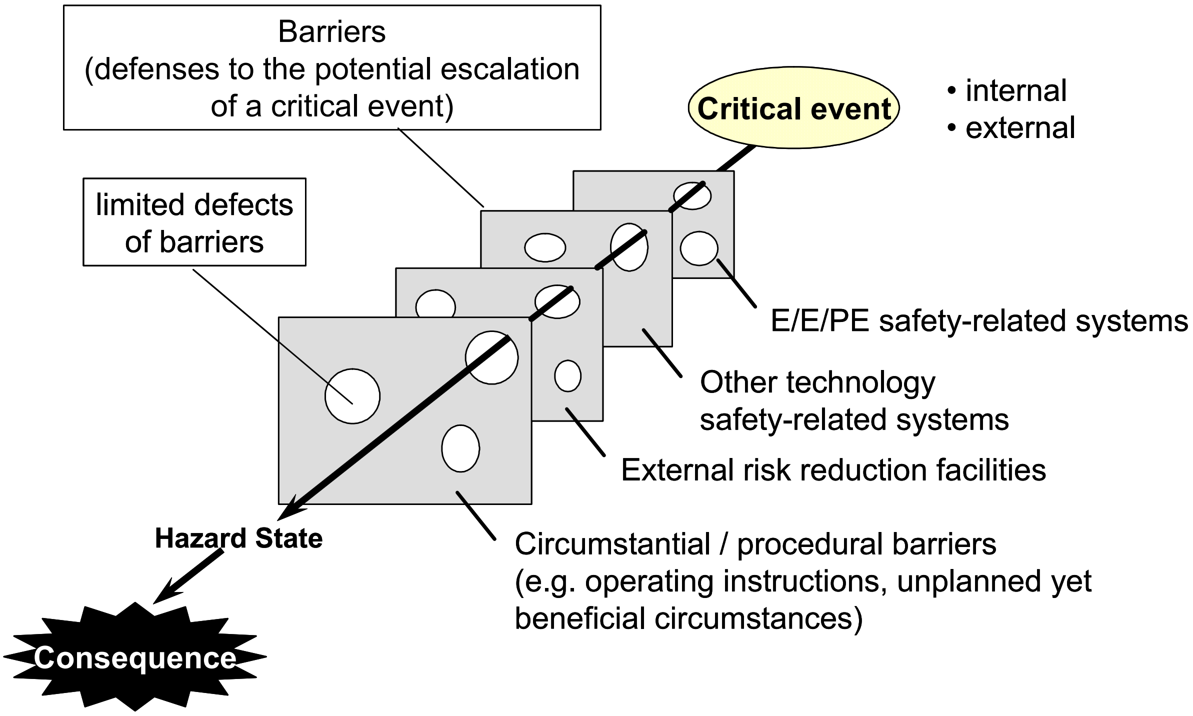


figure 3: Consequence Analysis

Consequence analysis summarizes the barriers which have to become active to avoid that a hazard develops into a damage state. Human actions acting as barriers can be treated in quite a similar way as technical failures by using human error probabilities which can be derived from data collections or described by so called operator action trees. Eventually, in order to determine the extent and type of consequence (i.e. harm, injury, and damage) in the case of hydrogen release, CFD-calculations, fire or explosion models and vulnerability models are used.

The risk analysis ends with statements about the likelihood of certain critical events and their resulting consequences, i.e. (simplified) with "points in the risk diagram" of figure 1. Each region of the diagram requires specific action: In the "unacceptable band" risk must be reduced at whatever costs. In the "acceptable region" little or no effort is justified to reduce it further. Some-where in between the procedures for measures can be characterized by the ALARP- (“as low as reasonably practicable”) principle. In the UK and the Netherlands, e. g., for process industry some form of Cost-Benefit-Analysis is recognized as a relevant approach to derive what is relevant and what is not.

What is the situation in the transportation sector?

3. Automotive Industry

Due to environmental aspects but also because of its (potentially) economic advantage, hydrogen is also investigated as alternative fuel for cars. During the last years, considerable progress has been made with respect to technical solutions and standardization.

With respect to safety, the situation is in principle very similar to aircraft industry with the difference that hydrogen vehicles are already in the field. An interesting example is the CUTE-Project (CUTE = Clean Urban Transport for Europe). The goal of this project is to demonstrate the real-world performance and economics of hydrogen for public transportation. The CUTE project involves nine cities in eight European countries, and is evaluating 27 hydrogen-powered buses in a variety of conditions.

The results of this and many other pilot projects as well as experiences manufacturers and suppliers are gathering with their internal solutions form the input for the standardization committees. The standardization process has made progress in the last years (for a summary see [5]), but is still not complete. The final goal is, of course, to make life easier for suppliers and manufacturers: Following the standards shall then imply that the associated risks are in fact tolerable. So we need two things: A risk target and experience that the target is met in practice.

But if series production with thousands of hydrogen cars shall start in the next decade, the statistical basis for incidents or accidents will probably be still too small to verify that the risk is tolerable. Such a target even does not exist here, in contrast to aircrafts (see chap. 4).

That’s why we applied another solution to define the tolerable risk target [6]: We compared the risk for the hazard of fire of a conventional car with the corresponding risk for fire or explosion for a hydrogen car. The argument was simply that the consequences – injured or even killed persons by fire or following an explosion in a car – are similar in effect and therefore *should* also be so in society’s perception (a similar approach, the GAMAB-Principle, has been formulated for railways, see ref. [7]).

The general strategy is shown in figure 4. Without optimization, the risk of new technical solutions usually will be higher than for the old solution, which, as we assume, was accepted by society. We must achieve that the new situation is (at least) “as good as before”. This means, we perform a comparative risk study.

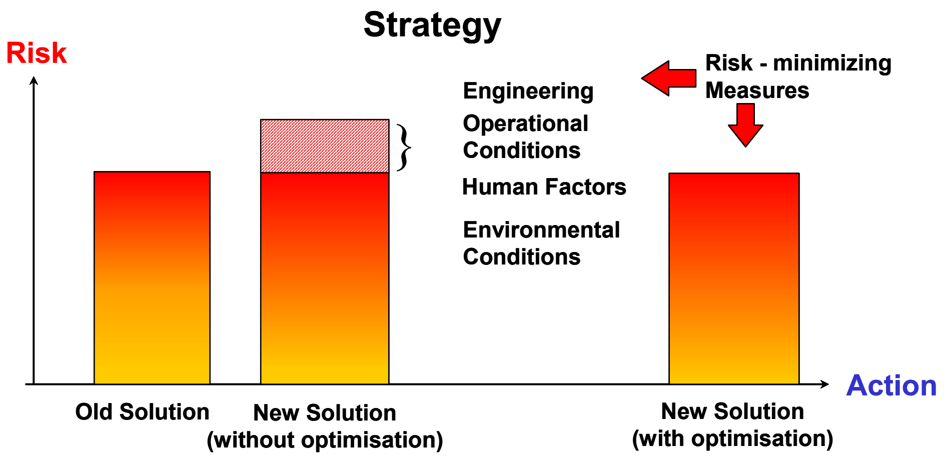


figure 4: General strategy for deriving a tolerable risk target (“as good as before”)

Realizing an identical level of safety does not a guarantee that the car is really accepted by society or its representatives, of course. But the criterion gives a hint whether it *could* be accepted and will be a well based argument for discussions, e.g. with authorities.

This approach of comparative risk analysis for cars cannot be adopted for aircrafts – the two “worlds” are just too different, essentially because cars are a mass product, whereas aircrafts are ordinarily not built in huge number of pieces. This fact has some important implications (among others, of course):

Aircraft crews are very well trained people and fully aware of safety-issues. Ordinary drivers usually do not read carefully operating manuals and just want to start their car and drive – otherwise, if they have to study lengthy safety instructions before driving, they will simply not buy such complicated equipment. Furthermore, the required level of safety for airplanes is kept up by employing special maintenance staff. Car drivers on the contrary are not even obliged to visit a garage, but may be tempted to repair off one’s own bat … That is, the user aspect is by far more relevant for cars than it is for aircrafts.

On the other hand, an accident involving an aircraft attracts more attention than a car accident. If hydrogen is the final cause of such an accident, the technology could be quickly refused by the public or at least scrutinized closely with economic consequences.

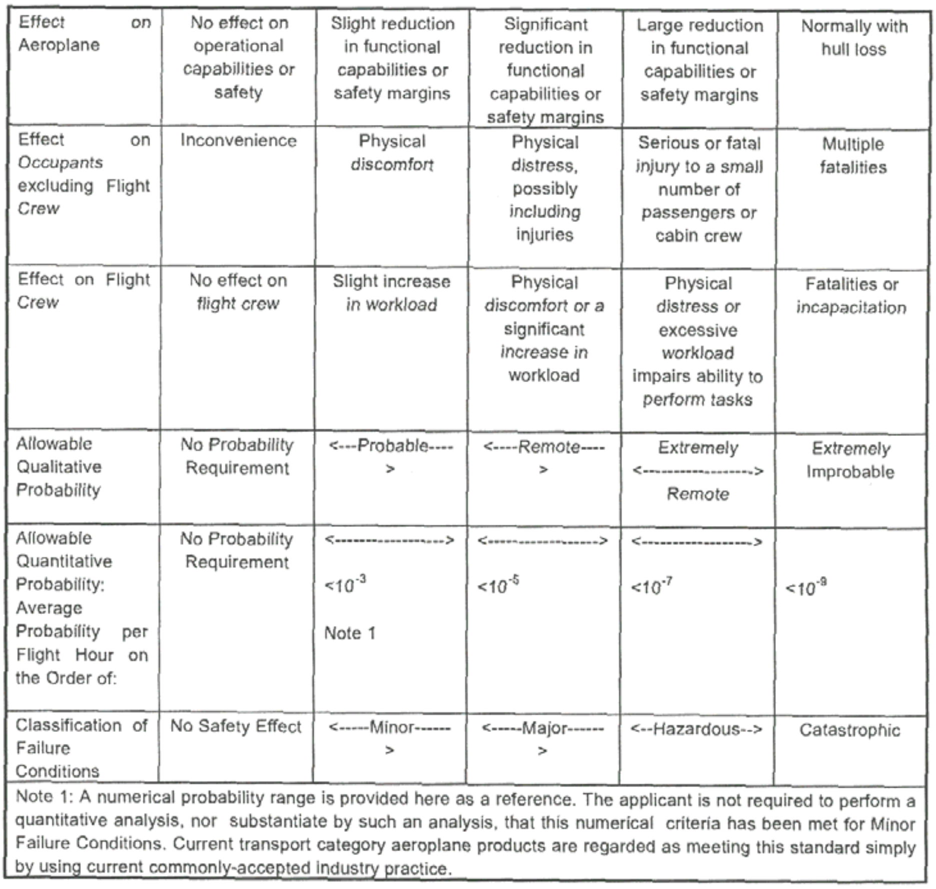
Correspondingly the safety requirements for automotive applications are in many ways very different compared to aircrafts. But there also some similarities, as we will see immediately.

4. Tolerable Risk Targets for Hydrogen in the Aircraft Sector

Tolerable risk targets are well defined in the aircraft industry which means a main difference to risk assessments for cars. FAA and EASA introduce the concepts of “Probability of Failure Condition” and the “Severity of Failure Condition Effects”. The relationship between them is such that

(1) Failure Conditions with no safety effect have no probability requirement.
(2) Minor Failure Conditions may be probable.
(3) Major Failure Conditions must be no more frequent than remote.
(4) Hazardous Failure Conditions must be no more frequent than extremely remote.
(5) Catastrophic Failure Conditions must be extremely improbable.

These qualitative descriptions are completed by quantitative targets, see table 1, [2].



Effect on Aeroplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants excluding Flight Crew	Inconvenience	Physical discomfort	Physical distress, possibly including injuries	Serious or fatal injury to a small number of passengers or cabin crew	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Allowable Qualitative Probability	No Probability Requirement	<---Probable---->	<----Remote---->	Extremely <------------------> Remote	Extremely Improbable
Allowable Quantitative Probability: Average Probability per Flight Hour on the Order of:	No Probability Requirement	<------------------> $<10^{-3}$ Note 1	<------------------> $<10^{-5}$	<------------------> $<10^{-7}$	$<10^{-9}$
Classification of Failure Conditions	No Safety Effect	<-----Minor------>	<-----Major------>	<--Hazardous-->	Catastrophic
Note 1: A numerical probability range is provided here as a reference. The applicant is not required to perform a quantitative analysis, nor substantiate by such an analysis, that this numerical criteria has been met for Minor Failure Conditions. Current transport category aeroplane products are regarded as meeting this standard simply by using current commonly-accepted industry practice.					

table 1: Relationship between Probability and Severity of Failure Condition [2]

Catastrophic failure conditions, i.e. conditions, which would result in multiple fatalities, usually with the loss of the airplane, are of special importance. The regulations in AMC 25.1309 (System Design & Analysis, corresponding to AC 25.1309-1A) [3], paragraph 8, read as follows:

"c. The safety objectives associated with Catastrophic Failure Conditions, may be satisfied by demonstrating that:

(1) No single failure will result in a Catastrophic Failure Condition; and
(2) Each Catastrophic Failure Condition is extremely improbable.

d. Exceptionally, for paragraph 8c(2) above of this AMC, if it is not technologically or economically practicable to meet the numerical criteria for a Catastrophic Failure Condition, the safety objective may be met by accomplishing all of the following:

(1) Utilising well proven methods for the design and construction of the system; and
(2) Determining the Average Probability per Flight Hour of each Failure Condition using structured methods, such as Fault Tree Analysis, Markov Analysis, or Dependency Diagrams; and
(3) Demonstrating that the sum of the Average Probabilities per Flight Hour of all Catastrophic Failure Conditions caused by systems is of the order of 10^{-7} or less (See paragraph 6a for background)."

It is now interesting to see that the argument given at the aforementioned paragraph 6a is rather similar to the approach we discussed above with regard to automotive applications:

"Historical evidence indicated that the probability of a serious accident due to operational and airframe-related causes was approximately one per million hours of flight. Furthermore, about 10 percent of the total were attributed to Failure Conditions caused by the aeroplane's systems. *It seems reasonable that serious accidents caused by systems should not be allowed a higher probability than this in new aeroplane design*s. *(Highlighted by authors)* It is reasonable to expect that the probability of a serious accident from all such Failure Conditions be not greater than one per ten million flight hours or 1 x 10^{-7} per flight hour for a newly designed aeroplane. The difficulty with this is that it is not possible to say whether the target has been met until all the systems on the aeroplane are collectively analysed numerically. For this reason it was assumed, arbitrarily, that there are about one hundred potential Failure Conditions in an aeroplane, which could be Catastrophic. The target allowable Average Probability per Flight Hour of 1 x 10^{-7} was thus apportioned equally among these Failure Conditions, resulting in an allocation of not greater than 1 x 10^{-9} to each. The upper limit for the Average Probability per Flight Hour for Catastrophic Failure Conditions would be 1 x 10^{-9}, which establishes an approximate probability value for the term 'Extremely Improbable'…"

We can now argue that for demonstrating that the implementation of a "new system", namely the "hydrogen system", is not an intolerable risk, we have to stay below the threshold of the "tolerable risk target" of 10^{-9}/flight-hour for the hydrogen system.

What is the hydrogen system in our case? For illustration, consider figure 5 which shows the principle of a fuel cell with hydrogen production by reforming. What must be analyzed in more detail are components like the reformer, the fuel cell or the piping system, but also the process control and monitoring system or safety instrumentation.

Existing concepts schedule a more or less complete enclosure of components or subsystems containing hydrogen. Furthermore, a completely autarkic system is planned, i.e.: All safety-related functions, e.g. controlled shut-off, must be performed fully automatically.

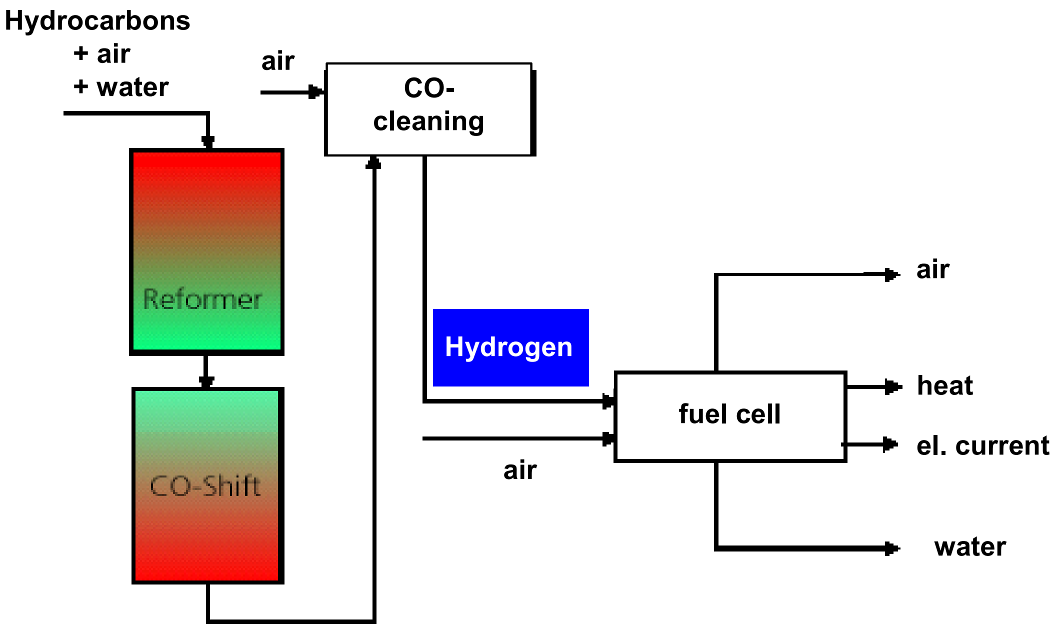


figure 5: Hydrogen production for fuel cell by reforming

To demonstrate that we achieve our risk target we have to perform an analysis in the form of figure 3 (paragraph 8d(2) and (3) of AMC 25.1309) and use well proven methods for the design and construction of the system (paragraph 8d(1) of AMC 25.1309).

What must be done to realize this strategy?

5. Implementation of Risk Strategy

The predominant hazard states which must be controlled and which are important for our point can be easily characterized and are similar to those in industrial fire protection [8]:

- Loss of Containment
  Prevention, isolation, or shutdown of releases from explosive or flammable gas transfer systems (piping, pumps, process equipments like the reformer, fuel cell etc.)

- Process Safe Operating limits
  Prevention of process deviations (i.e. operating outside safe operating limits) that could lead to over-temperatures, overpressures and as a consequence loss of containment of process materials, e. g. hydrogen from the reformer in our case

Therefore, we first have to judge or estimate the probability of these states. To do so, the special design of the hydrogen-system and relevant components (e.g. FC, valves, piping) must be defined. In the moment, generic data are essentially available just for stationary equipment; component specific data have not been published up to now, the statistical basis would probably be too small anyway. This means an inevitable inaccuracy for the final results which must be evaluated.

In principle, we have two types of barriers which prevent the hazard states from escalating into a real damage:

- Ventilation and inerting
  Prevention and control of flammability and combustible or explosive mixtures stemming from process upsets and loss of containment

- Emergency Control Systems (ECS)
  Used for pre-fire or pre-explosion mitigation and designed to control, isolate or shut down process equipment following detection of an abnormal event situation – the release of hydrogen due to failures of the enclosure in our case.

Again, the judgment on these systems depends on the actual design. Their application and functional performance requirements will depend on the defined specific scenario and the established risk tolerance criteria.

To meet these performance levels, reference to IEC 61508 [4] can be made for the ECS. The standard treats safety instrumented systems (SIS) in general terms. A SIS is generally composed of sensors, logic systems and actors for the purpose of taking the system to a safe state when predetermined conditions are violated (figure 6).

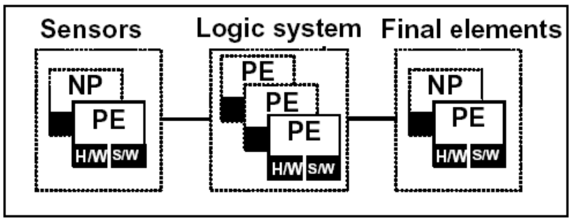


figure 6: General architecture of a SIS (from [4], part 2; examples include single or dual channel and “m out of n” redundancies); PE programmable electronics, NP non-programmable devices

What performance can we expect? To illustrate this point let’s take as a (very) simplified example the release of hydrogen by a leakage within the hydrogen system. The system is designed in such a way that a sensor detects gas and then activates the fire protection system. From a “classical point of view” the problem of hydrogen leakage is solved and the safety functions (sensor, protection system) are built, maintained and implemented according to the “state of art” (in reality, the design described here would not be sufficient from a “classical point of view”, of course).

For a quantitative risk analysis we first have to find appropriate data. Let’s take the following plant failure data which are derived from a LNG plant [9]:

System	Operating or In service* hours	Major failures	λ [h^{-1}]	Remarks
Hazard detection systems (sensors in figure 6)				
- Gas detectors	16,703,000	44	$2{,}6 \cdot 10^{-6}$	
- High temperature detectors	8,418,000	0	$5{,}9 \cdot 10^{-8}$	Bayes approach
Fire protection systems (final elements in figure 6)				
- Gas system	364,000*	2	$5{,}5 \cdot 10^{-6}$	
- Foam system	88,000*	0	$5{,}7 \cdot 10^{-6}$	Bayes approach

table 2: SIS-data [9]

For the Logic System we assume an arbitrary value of $1 \cdot 10^{-7}$/h and for all components a test period of one year. From table 3 we find that the SIL of the logic system is about 2 or 3, for the sensor and the final element it is SIL 1.

Safety integrity level	**Low demand mode of operation** (Average probability of failure to perform its design function on demand)
4	$\geq 10^{-5}$ to $< 10^{-4}$
3	$\geq 10^{-4}$ to $< 10^{-3}$
2	$\geq 10^{-3}$ to $< 10^{-2}$
1	$\geq 10^{-2}$ to $< 10^{-1}$

table 3: Safety integrity levels (SIL): target failure measures for a safety function, allocated to an E/E/PE safety related system operating in low demand mode of operation (from [4], part 1)

If the system forms a simple series connection, we find for the total architecture again SIL 1. To judge whether this is "sufficient" we further assume that the ECS (or SIS) must guarantee a risk reduction of about 100 or more, corresponding to SIL 2. In this case, we can conclude that a second and redundant gas sensor and redundant fire protection systems are indispensable. A detailed investigation with respect to qualification and reliability of the components could also show that halving the periodic testing interval for sensor, logic and final element are further possible solutions.

The essential point is that we can now decide on a sound basis what to do. And even more, we can take the input data (which might look strange – what has a LNG-plant to do with hydrogen in the air?) and use them as reliability requirements for our suppliers – at least with respect to failure rates (of course, other items like EMC, ambient and medium temperature and pressure, vibrations etc. are also very important input variables for this purpose). For a more detailed discussion of standardization and certification see ref. [5].

But another aspect is also important: Boeing and Airbus define many of the technical specifications for their planes based on their own internal standards. One should be aware of the fact, however, that aircraft industry cannot develop “stand-alone-solutions” without referring to well established codes like [4] – at least when introducing complete new technology with safety relevance. It wouldn’t be even wise to do so just because these regulations should not be regarded as formal restrictions only but also as transparent basis for developers on the part of the suppliers and manufacturers.

6. Summary

Considering the present situation of introducing hydrogen in the aircraft industry, we draw the following conclusions:

- ***Experiences*** with hydrogen in the automotive (and other) sectors are only partly of use for aircrafts with respect to technical boundary conditions and the qualification of users.

- ***Standardization*** is on the way, but there is no obvious cooperation of the big manufacturers (in contrast to the automotive industry).

- There seem to be **no fundamental difficulties** with the introduction of hydrogen for aircrafts with the regard to the technical equipment to be used.

- **More detailed analyses** of the
    - process technology to be used,
    - E/E/PES and
    - fire protection measures

  are still necessary to guarantee the required level of safety. Insofar also learning from existing solutions (also from the automotive sector) is encouraged, with regard to engineering and standardization.

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