HYDROGEN TECHNOLOGY – READY FOR TAKE-OFF – HYDROGEN APPLICATIONS IN AEROSPACE INDUSTRY

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Abstract

We will present an overall approach including 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. We develop general ideas and proposals for implementing fuel cells for aviation. Doing so, we refer to already existing experiences in process plants and to the state of standardisation in related fields like automotive sector. It is shown that the technical and formal prerequisites for introducing hydrogen technology for aviation are given and that the further discussion can focus now on details.

1 Introduction

Hydrogen is considered an alternative fuel for two reasons: It is 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 simple combustion (internal combustion engines, ICE's, or turbine engines) or by converting it to electricity in a fuel cell. Research and development projects have demonstrated that using compressed hydrogen or liquid hydrogen is feasible today. Therefore, hydrogen also gets a very important status for aviation. On the other hand, 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 [2003] [1] FAA, EASA) 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 (FAA, EASA). 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 fly-fix-fly 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. We now have to face some new situations if applying hydrogen for commercial aircrafts. Adjustments in manufactured parts and components will be necessary to handle e. g. cryogenic liquid hydrogen with a temperature range from -150°C to -273°C. This means that experiences in related fields of application must be used which are not specific for aircrafts. Furthermore, there is no long-term experience (or no experience at all) whether these experiences can be "translated" and applied to commercial aircraft industry. And 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. 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 our paper 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.

2 Basic Concepts of Risk Analysis

2.1 General Remarks and Definitions

Starting our discussion with talking about risks might look strange in this context, simply because "risk" is generally accompanied by negative associations. Engineers often refuse to accept it in their sphere of responsibility: It seems that in the same moment when we admit risky consequences of our activities we admit that errors and faults could have been committed. In fact, "Risk" is a term widely used in the everyday life and in the scientific world. For example, in everyday conversation it could be said that "the risk of death by a falling meteorite is very low, whereas the risk of being infected by flu during the winter is quite high". Similarly, an engineer will confirm that the risk of an airplane falling is very low and a psychologist will try to explain human reactions to risk. It appears that in almost each and every field of science the term has a different meaning. Thus, there is a need to clarify the concept of risk and to explain the way how it is defined. This helps us to give the word a precise and objective meaning and use it in a reasonable way instead of giving the impression that "nothing will happen". Following IEC 61508 [2] risk can be defined as combination of the probability of occurrence of undesirable consequences and their severity. 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:

$$\mathit{Risk} = \mathit{Likelihood} \cdot \mathit{Undesirable\ consequences} \quad (1)$$

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:

$$\log(\mathit{Likelihood}) + \log(\mathit{Consequence}) = \mathit{const.} \quad (2)$$

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

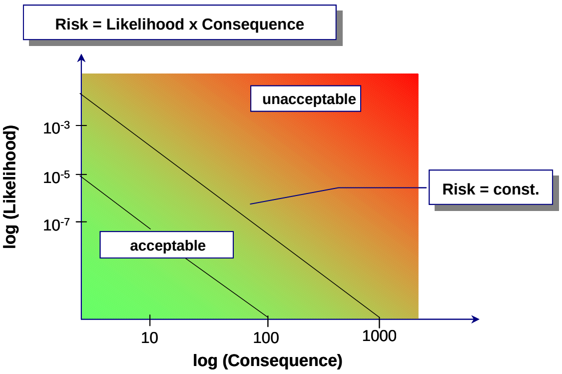


Fig.1 General risk diagram

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 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 (IEC 61508). Safety can be realized by different protective measures. In other words, in respect of a specific hazardous event, we need functions to be implemented by technical systems (e. g. electrical/electronic/ programmable electronic (E/E/PE) systems), which are intended to achieve or maintain a safe state for the system (see Fig.2) These functions are also called "safety functions" (IEC 61508). Again following IEC 61508, the part of the overall safety relating to the system (or "equipment under control", EUC in Fig.2) and the EUC control-system which depends on the correct functioning E/E/PE safety-related systems, other technology safety-related systems and external risk reduction facilities is defined as functional safety. Finally, safety integrity is the probability of a safety-related system satisfactorily performing the required safety functions under all stated conditions within a stated period of time.

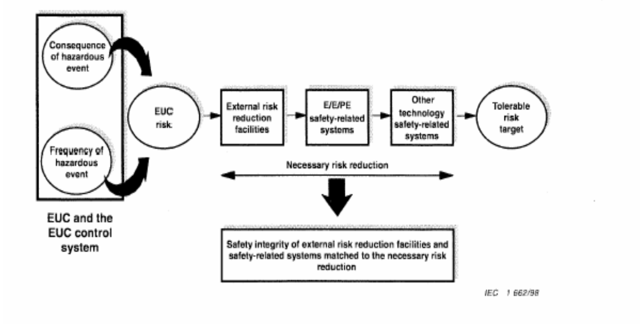


Fig.2 Risk and Safety Integrity

The general principle of performing a risk analysis is shown in Fig.3 below: Starting with a causal analysis, one first has to identify and characterize the hazards and failure modes of the components or external events which lead to the hazard. 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 (see, e. g., Kirchsteiger [1998], [3]). 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.

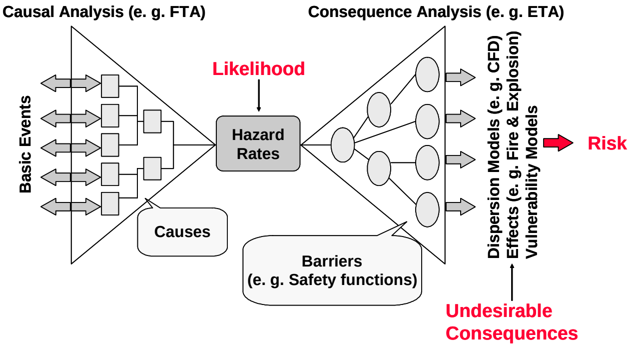
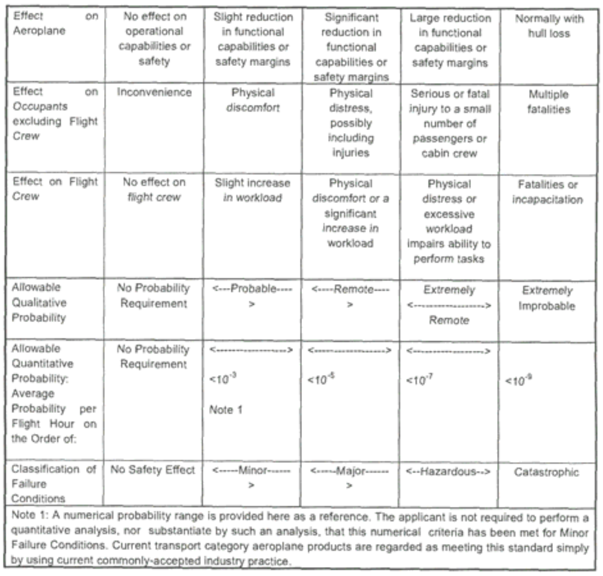


Fig.3 Causal Analysis and Event Tree Analysis

The way from the hazard rates to the consequences via event trees is also shown in Fig.3. Event trees summarize the barriers which have to become active to avoid that a hazard develops into a hazard state. The unavailability of technical safety functions again can be quantified with numerical data just as before for the causes of the hazards. Furthermore, we can add human actions as barriers. These actions 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 consequences (i.e. harm, injury, damage) in the case of gas release, CFD-calculations, fire or explosion models and vulnerability models can be used. The risk analysis ends with statements about the likelihood of certain events and their resulting consequences, in simple words: With “points in the risk diagram” of Fig.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. Somewhere 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., some form of Cost-Benefit-Analysis is recognized as a relevant approach for certain types of safety-related decision. In the case of hydrogen in the automotive sector, we have applied another solution to define the tolerable risk target (see Fig.2): 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 in a car – are actually similar in effect and therefore also in society’s perception. This is of course not a guarantee that the system is really accepted by society or its representatives, but the criterion could at least give a hint whether it could be accepted and a well based argument for discussions. How could we proceed in the analogous case for aircrafts in a situation which is, of course, in many ways very different compared to automotive applications?

2.2 Tolerable Risk Targets in the Aircraft Sector

Until now, we have discussed from the viewpoint of actual standardization in the form of IEC 61508. But procedure applied there is completely compatible with corresponding regulations of EASA and FAA: e. g., the following table 1 is taken from [13].



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.					

TAB 1. Relationship between Probability and Severity of Failure Condition [13]

The relationship between the “Probability of Failure Condition” and the “Severity of Failure Condition Effects”, as shown in table 1 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.

Catastrophic failure conditions, i.e. conditions, which would result in multiple fatalities, usually with the loss of the aero plane, are of special importance. The regulations in AMC 25.1309 (System Design & Analysis, corresponding to AC 25.1309-1A) [4], 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 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 airplane's systems. It seems reasonable that serious accidents caused by systems should not be allowed a higher probability than this in new aero plane designs. 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 aero plane. The difficulty with this is that it is not possible to say whether the target has been met until all the systems on the aero plane are collectively analysed numerically. For this reason it was assumed, arbitrarily, that there are about one hundred potential Failure Conditions in an aero plane, 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 a risk, we have to stay below the threshold of the "tolerable risk target" of 10^{-9}/flight-hour. To do so, we have to perform an analysis in the form of Fig.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 realise this strategy?

3 Implementation of Risk Strategy

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 the shut-off valves are activated by the sudden pressure drop in the pipe. The leakage is then isolated. If they fail to close a gas sensor can detect H2, then activates a limit indicator which in turn starts a relay so that a fan starts. From a "classical" point of view the problem of hydrogen leakage is solved and the safety functions (shut-off valves, sensor, fan) are realized according to the "state of art". A quantitative risk analysis could now tell us that the equipment is so important that a second and redundant gas sensor is indispensable. Furthermore, a detailed investigation with respect to qualification and reliability of the components could show e.g. that the periodic testing interval for sensor, indicator and fan should be reduced. The physical and chemical properties of gases such as hydrogen and the possible hazards associated with their use call for specific safety features. The level of safety for the production and utilization of hydrogen depends on many factors. While results from research and development, experience from operations and quality standards form the basis, legal and social requirements also need to be taken into account. Moreover, drawing up a safety concept requires a detailed system analysis and risk assessment. In order to optimise the safety level, a close look has to be taken at

- the state of components and systems,
- possible impacts of specific hazards
- the capacity and size of components and safety devices
- operational parameters like training, inspecttions, maintenance and repair strategies.

All of these measures are taken to ensure that the safety level is equal to that of conventional fuels. Only if that is the case, public acceptance can be brought about. In chapter 6 we discuss how to apply safety analysis in general framework of certification.

4 Hydrogen and Fuel Cells – Codes and Standards

Roughly 120 years after the invention of the fuel cell, it was space travel that paved the way for the utilization of this form of technology. Functionality and reliability were considerably more important than the relatively high costs for fuel cells. By increase of experience and decrease of costs fuel cells became more and more interesting for other applications. The current trend towards energy efficient planes is driving the further development of on-board components and systems. Especially known for their energy efficiency fuel cells will be one of the main key technologies to achieve this goal. Fuel Cells generally run on hydrogen which is mainly produced from different hydrocarbons using reformers. For aircrafts, no rules, codes or standards for fuel cells or hydrogen applications exist. Therefore it makes sense to take a look into existing rules and codes used to prove safety and reliability of gas systems in general, fuel cells and hydrogen in this case. These are mainly developed by chemical industry for process plants for stationary use. Today, automotive industry pushes the set up of specific codes and standards in order to introduce hydrogen into the transportation sector. Therefore, it is useful to have a closer look on the standardization activities in this field. Furthermore, we give a short overview over codes and standards which are currently developed for hydrogen applications.

4.1 Rulemaking – the Automotive Approach

Automobile industry decided to go new ways by using gas in the propulsion system of vehicles. For this reason the automotive industry took compressed natural gas (CNG), liquid natural gas (LNG) as well as liquefied petroleum gas (LPG) systems into account for propulsion in ICE´s. Some years later systems running on hydrogen started as well. While developing this kind of gas systems some years ago automotive engineers, manufacturer of cars and components felt a real drawback for hydrogen technology in mobile use by realising the following problems:

- there are already certain legal requirements before a vehicle can be approved and registered for use in different countries
- Vehicle and component manufacturer needed uniform legal requirements throughout the world to speed development and reduce costs
- when there is no legal existing requirement within e.g. Germany, the EU or even US there will be a special approval required combined with different requirements of every authority and time consuming deviations

- even the outcome is sometimes uncertain until the end of the process

To overcome these problems in February 1998 a project called EIHP (European Integrated Hydrogen Project) [5] was established. One part of the project - a quasi top-down-approach - was focused on the existing hydrogen-related legislation in European countries. Adequate legislation scarcely existed in these days, particularly in the field of licensing procedures for hydrogen vehicles. Correspondingly, a structured survey and analysis of existing relevant rules, regulations and licensing procedures in the participating countries (Belgium, France, Germany, Spain and Sweden) has be conducted with the aim of not only identifying deficiencies but also defining regulations which were already sufficiently comprehensive to facilitate harmonization throughout Europe. The other part of the project – a bottom-up-approach – was focused on existing hydrogen vehicles in Europe including the infrastructure supply technology. Systematic analyses such as Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), Hazard Operability Studies (HAZOP) etc. have been conducted and complemented by detailed studies of worst-case scenarios. This helped to document safety features while systematically improving the potential of hydrogen technology, thus creating a more solid basis for discussion with relevant licensing authorities. In February 2001 a second phase of this project started:

EIHP2 did also develop a refuelling station layout requirement, analyse and quantify health, environment and safety risks associated with onsite hydrogen equipment and assess the requirements for maintenance and periodic inspection of all related components and systems. Finally, EIHP2 identifies the requirements necessary to harmonise standards, codes of practice and filling procedures applicable to refuelling station sub-systems and components on a European and global level. For the first time this will also include the refuelling interface (nozzle-receptacle) between the filling station and the vehicle also taking into account the necessary refuelling procedures for fast filling. EIHP2 tries to undertake comparative risk and safety analyses with respect to the release of hydrogen in confined and semi-confined environments, such as tunnels, inner-city streets and garages. These experimental data shall provide sufficient input to enable the partnership to define the required inputs for hydrogen related standards and regulations. EIHP2 in its attempt for global harmonisation tries to coordinate such activities between the EU and the USA. Also first contacts to Japan have been established.

4.2 Present status of Codes and Standards

As well as in automotive use codes and standards for further hydrogen applications are in the phase of construction: In this context we have to name first of all the ISO TC 197 (Hydrogen technologies, [6]) with following working groups:

WG1:	Liquid hydrogen - Land vehicles fuel tanks
WG2:	Tank containers for multimodal transportation of liquid hydrogen
WG4:	Airport hydrogen fuelling facility
WG5:	Gaseous hydrogen blends and hydrogen fuels - Service stations and filling connectors
WG6:	Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks
WG7:	Basic considerations for the safety of hydrogen systems
WG8:	Hydrogen generators using water electrolysis process
WG9:	Hydrogen generators using fuel processing technologies
WG10:	Transportable gas storage devices - Hydrogen absorbed in reversible metal hydride
WG11:	Gaseous hydrogen - Service stations
WG12:	Hydrogen fuel - Product specification

and IEC TC 105: Fuel Cell Technologies [7] with the following working groups:

WG 1:	Terminology
WG 2:	Fuel cell modules

WG 3: Stationary fuel cell power plants – Safety
WG 4: Performance of Fuel Cell Power Plants
WG 5: Stationary Fuel Cell Power Plants - Installation
WG 6: Fuel cell system for propulsion and auxiliary power units (APU)
WG 7: Portable fuel cell appliances - Safety and performance requirements

In addition to this completely new codes and standards we have to take into account that there are results and know how already available about handling hydrogen in all phases from production, storage, filling and utilisation. These know how was built up and step by step fixed in state of the art rules. These rules should be used e.g. to calculate the design of cylinder for hydrogen storage or to prove the wall thickness and the material of valves for pressure application. Last but not least measures to enforce accident prevention for maintenance have to be taken into action as described and laid down in several different national regulations.

5 Hydrogen and fuel cell application in aviation

Several thermochemical and kinetic factors make hydrogen attractive as the next industrial and transportation fuel as well in automobile use as in aviation. The use of normal combustion engines running on hydrogen for propulsion on one hand or the use of fuel cells to convert fuel into electrical current, heat and water on the other hand are both policies for near future.

Combustion Engine

Using hydrogen as fuel for combustion jet engines in order to propel the airplane is one way. In form of a concept study the “Cryoplane-Project” [8], based on an Airbus A310, showed the principal feasibility of hydrogen-driven airplanes. The major advantage of this is the reduction of exhaust gases because there are no other pollution than nitrogen oxides and steam. Connected to this there are no longer carbon dioxide and other pollutants emitted. For this purpose only some slight modification of jet engines had to be conducted.

Fig.4 Conversion of a 328Jet [8]

A demonstration project on the basis of the 328Jet is now going to be realized.

Fuel Cells

Fuel cells run on hydrogen. The great advantage of fuel cells is that they do not care where the hydrogen comes from. Various forms of hydrocarbons are feasible as fuel: natural gas, gasoline, methanol, ethanol or even kerosene. Fuels containing hydrogen generally require a "fuel reformer" that extracts the hydrogen. Three basic reformer designs are being evaluated for fuel cells in automobile application: steam reforming, partial oxidation and auto-thermal reforming.

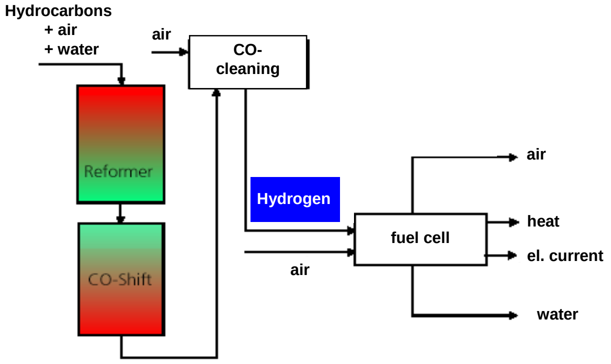


Fig.5 fuel cell system with reformer [9]

Differences in the chemical nature of the fuels, however, can favor one design over another.

6 Fuel Cell Systems for Airplanes

A fuel cell system must be integrable into existing airplane systems and furthermore integrated into the available ATA-System (Air

Transport Association of America, ATA) [11]. It is common practice in civil aviation to group aircraft systems according to Specification 100 of the ATA. This specifications aim to thoroughly structuring aircraft documentation.

What are Aircraft Systems?

Broadly speaking, an aircraft can be subdivided into three categories:

1. the airframe (the aircraft structure)
2. the power plant (the engines)
3. the aircraft systems (the equipment).

Aircraft systems comprise all mechanical, electrical and electronic items, devices and components, which are installed in an aircraft. Systems on board of airplanes must reach some specific requirements. These Requirements on Aircraft and fuel cell systems are:

- Performance requirements (dependent on respective system)
- Certification requirements
- Reliability requirements
- Request for maintainability
- Request for small mass and small floor space required
- Request for small operating and acquisition costs
- Environmental Conditions

The term "system" is frequently used in engineering sciences. In thermodynamics, for example, a system is characterized by its defined boundary. The definition of the term "system" with respect to aviation is a little more specific. The World Airlines Technical Operations Glossary (WATOG) [10] defines:

System:	A combination of inter-related items arranged to perform a specific function. (WATOG 1992)
Subsystem:	A major functional portion of a system, which contributes to operational completeness of the system. (WATOG 1992)

A comparison between the system structure of an APU (system, subsystem, component, subassembly to one single part) with that of a fuel cell (used in cars or in an aircraft) we can find the same systematic structure.

	APU	**Fuel cell for cars**	**fuel cell for aircrafts**
system	auxiliary power unit	fuel cell	fuel cell
subsystem	power generator	fuel cell stack	fuel cell stack
component	fuel control unit	"fuel" control unit	"fuel" control unit
subassembly	valve	valve	valve
part	seal	seal	seal

TAB 2. Comparability of an APU and fuel cell (according to WATOG)

Fuel cell systems consist generally of numerous quantities of subsystems, components, subassemblies and parts. A list of relevant subsystems a fuel cell consists of is given here:

- Fuel supply
- Reformer
- Gas conditioning and gas cleaning
- Fuel cell stack
    - Electrical equipment
    - Control unit
    - Systems for the heat decoupling
    - Electric network

7 Aspects of Certification

After one or several prototype aircrafts are designed and manufactured, they go through a series of certification tests in order to show compliance with the certification requirements. Compliance with the requirements may be shown by analysis, ground, or flight test, depending on the requirements or negotiations with the aviation administration. System test are substantial part of the certification program. In Europe, certification of large airplanes is based on the Joint Aviation Requirements but since 2003, the JAA was dissolved by the EASA. EASA is one of the European Community's 15 agencies. Agencies are distinct from the Community Institutions (Council, Parliament, Commission, etc.) and have their own legal personality. They are set up by an act of secondary legislation (the Basic regulation) in order to accomplish a very specific technical, scientific or managerial task which is specified in that act. EASA has been given defined responsibilities and tasks with respect to civil aviation safety and environmental sustainability. Except for the limited rules established by the Community in the field of airworthiness and maintenance through Regulation 3922/91, Member States were responsible for the regulation of civil aviation safety. Although they did their best to harmonize their requirements and practices in the Joint Aviation Authorities, this system led to differing interpretations of harmonized standards, which adversely affected the efficiency of regulation and increased compliance costs for the sector. Although the European Commission has been closely associated with the JAA process, it is hoped that a transition to the EASA system and decision-making based on the European Community method will mark a significant improvement in the execution of certification and rulemaking tasks. It should also reduce fragmentation at the international level, by providing the international aviation community with a European interlocutor with enhanced authority and credibility. JAR-25 [12] / EASA CS-25 [13] and in the United States it is based on the Airworthiness Standards: Transport Category Airplanes (FAR Part 25 [4]). Large airplanes are those aircraft with a maximum takeoff mass of more than 5700kg. EASA, JAR and FAR are very similar, the basic code for JAR-25, CS-25 is FAR Part 25 and further harmonization of the requirements is in progress. The certification of one or several prototype aircraft leads to a type certificate being issued. Aircraft in series production have to show airworthiness and conformity with the prototype aircraft. In service the aircrafts have to be maintained according to an agreed maintenance schedule to prove continuous airworthiness. JAR-25, CS-25 and FAR Part 25 are grouped into several subparts (the following is based on JAR-25, CS-25). Subpart F, „Equipment“, contains many requirements for aircraft systems. Subpart E, „Power Plant“, contains requirements for power plant related systems. Also Subpart D, „Design and Construction“, contains requirements for aircraft systems. Subpart J, „Gas Turbine Auxiliary Power Unit Installation“, contains requirements for airborne auxiliary power – i.e., auxiliary power unit (APU). General information on aircraft systems can be found in section 1301 „Function and installation“ and section 1309 „Equipment, systems and installations“ of JAR-25 (new EASA CS-25) and FAR Part 25. Section 1309 provides information on safety requirements, loads and environmental conditions. These regulations provides access to the Certification requirements for large airplanes when specific information related to a particular aircraft system is needed. Interpretative materials to most paragraphs is provided by

- FAR: Advisory Circulars (AC) (especially in AC25-17 and AC 25-22)
- JAR: Advisory Circular Joint (ACJ) (ACJ-25) and Advisory Material Joint (AMJ) (AMJ-25)

The Agency is currently consulting interested parties on the contents of Certification Specifications with respect to IR Certification. The consultation process is being carried out in co-operation with the Joint Aviation Authorities. For details of which texts are open to consultation and an indicative timetable, please refer to the JAA website. Completed texts shall be posted here as and when they are ready for publication.

Certification requires a structured process, as we have seen. But with no international rules for the application of fuel cells in airplanes at hand, we first have to consider the correct field of activity in order to attend all technical requirements for related systems in aviation before we can answer the question “how to get fuel cells flying". This in turn requires an answer to the following question:

What is a fuel cell? Is it a battery or a generator?

A fuel cell uses a chemical reaction to provide an external voltage, as a battery. But a fuel cell differs from a battery in that the fuel is continually supplied in the form of hydrogen and oxygen gas. Fuel cells produces electric current, heat and water and can therefore considered as more as a generator than just as a battery which is only charged and discharged. Fuel cells bear more resemblances to an APU (auxiliary power unit) than to any other system integrated in an aircraft. However in order to save time and money we can now refer to the existing rules and experiences. Since the fuel cell (FC) is just a kind of generator the task is to develop a new fuel cell regulation "CS-FC" on the basis of the CS-APU [14], CS-E [15] and in connection with ongoing rules from automobile manufacturers and already existing regulations of process industry. In this case, the most important points are **reliability** consideration, **safety** of the system and a consideration of the **critical parts**: The general concepts of reliability and safety have already been discussed in chapter 1. To apply the results of the corresponding analysis, some specific guidance is necessary.

7.1 Specific Guidance

7.1.1 Classification of Effects of FC Failures.

The failure classifications for aircrafts are not directly applicable to FC assessments since the aircraft may have features that could reduce or increase the consequences of an FC failure condition. Additionally, the same FC may be used in a variety of installations, each with different aircraft-level failure classifications. Since aircraft-level specifications for individual failure conditions may be more severe than the FC – level specifications, there should be early co-ordination between the FC manufacturer and the aircraft manufacturer to ensure FC and aircraft compatibility, especially for assessing cases where FC availability is essential to the continued safe flight.

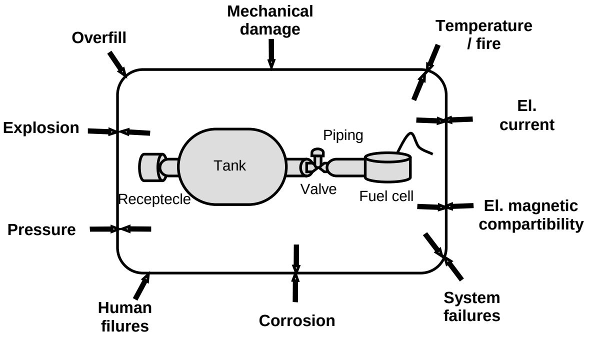


Fig.6 Safety of Gas Systems – General Concept [9]

7.1.2 Component Level Safety Analysis.

In showing compliance with CS-APU 210 [14], a component level safety analysis may be an auditable part of the design process or may be conducted specifically for demonstration of compliance with this rule.The specific specifications of CS-APU for the APU Control System also hold for FC Control System and should be integrated into the overall FC safety analysis.

7.2 Engineering, Manufacturing and Service of Critical Parts

As a result of safety analysis the safety relevant components (critical parts) and their respective failure modes are identified. For the critical components the integrity specifications must be derived. Following CS-E 515 [15] an Engineering Plan, a Manufacturing Plan and a Service Management Plan are required. These three plans define a closed-loop system which link the assumptions made in the Engineering Plan to how the part is manufactured and maintained in service; the latter two aspects are controlled by the Manufacturing and Service Management Plans respectively. These plans may generate limitations which are published in the Airworthiness Limitation Section of the Instruction for Continued Airworthiness. The Engineering Plan, Manufacturing Plan and Service Management Plan should provide clear and unambiguous information for the management of the Engine Critical Parts. „Plan“, in the context of CS-E 510 [15], does not necessarily mean having all technical information contained in a single document. If the relevant information exists elsewhere, the plan may make reference to drawings, material specifications, process specifications, manuals, etc., as appropriate. It should be noted that these references should be clear enough to uniquely the referenced document. The plan should allow the history of the individual part number to be traced.

7.2.1 Engineering Plan

The Engineering Plan consists of comprehensive life assessment processes and technologies that ensure that each Engine/fuel cell Critical Part can be withdrawn from service at a life before Hazardous Engine/fuel cell Effects can occur. These processes and technologies address the design, test validation and certification aspects as well as define those manufacturing and service management processes that should be controlled in order to achieve the Engine/fuel cell Critical Part design intent.

- Elements of the Engineering Plan
- Establishment of the Approved Life-General
- Establishment of the Approved Life-Static, pressure load parts
    - Tests
    - Analytical Modeling Methods
- Establishment of the Approved Life-Other Parts
- Maintaining the Approved Life
- Influencing Parts

7.2.2 Manufacturing Plan

The manufacturing Plan is a portion of the overall integrity process intended to ensure the life capability of the parts. The Engineering Plan includes about how Engine/fuel cell critical Parts are designed, manufactured, operated and maintained: each can an impact on the part life capability. Therefore, it is essential to ensure that the Attributes required by the Engineering Plan are maintained.

- Development and Verification of the Manufacting Plan
- Engineering (Design & Lifing)
- Material Engineering
- Non-Destructive Inspection
- Quality Assurance
- Manufacturing Engineering (development & Production)

7.2.3 Service Management Plan

The Service Management Plan forms part of the overall process intended to maintain the integrity of Engine/fuel cell Critical Parts throughout their service life.

- Determining the acceptability of repair and maintenance processes
    - Engineering (Design & Lifing)
    - Material Engineering
    - Non-Destructive Inspection
    - Quality Assurance
    - Product Support Engineering
    - Repair Development Engineering
- Service Management Aspects of Static Pressure Loaded Parts or Other Parts

7.2.4 Airworthiness Limitations Section (ALS)

The airworthiness limitations have been substantiated based on engineering analysis that assumes this product will be operated and maintained using the procedures and inspections provided in the instructions for continued airworthiness supplied with this product by the Type Certificate holder, or its licensees.

8 Conclusion

In this paper we develop general ideas and proposals for implementing fuel cells for aviation. Doing so, we try to refer to already existing experiences in process plants and to the state of standardisation in related fields like automotive sector. Furthermore, the existing safety philosophy and certification procedures for aviation are taken into account. It is shown that the technical and formal prerequisites for introducing hydrogen technology for aviation are given and that the further discussion can focus now on the details.

Abbreviations

AC	Advisory Circular
ADR	Accord européen sur le transport des marchandises dangéreuses par route
ALS	Airworthiness Limitations Section
ALARP	as low as reasonably practicable
AMC	Acceptable means of compliance
APU	Auxiliary Power Unit
ATA	Air Transport Association of America
CFD	Computational Fluid Dynamics
CNG	compressed natural gas
CRD	Comment Response Document
CS	Certification Specifications
EASA	European Aviation Safety Agency
E/E/PE	electrical/electronic/programmable electronic
EIHP	European Integrated Hydrogen Project
ETA	Event Tree Analysis
EUC	equipment under control
FAA	Federal Aviation Administration
FAR	Federal Aviation Requirements
FC	fuel cell
FH	flight hour
FMEA	Failure Mode and Effect Analysis
FMVSS	Federal Motor Vehicle Safety Standards
FTA	Fault Tree Analysis
HAZOP	Hazard Operability Studies
H_2	hydrogen
ICAO	International Civil Aviation Organisation
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
JAA	Joint Aviation Authorities
JAR	Joint Aviation Requirements
LNG	liquid natural gas
LPG	liquefied petroleum gas
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PEM	Protonen leitende Elektrolytmembran
RBD	Reliability Block Diagram
SAE	Society of Automotive Engineers
SOFC	Solid Oxide Fuel Cell
TÜV	testing and research laboratory
WATOG	World Airlines Technical Operations Glossary
WG	working groups

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