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Analysis of specific failure conditions in electrified propulsion systems using cryogenic hydrogen as a primary energy carrier

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Abstract
In order to minimize emissions of the aerospace sector and thus its impact on the climate, several novel concepts of propulsion systems for aircraft are being developed. Many of these concepts do not use an energy source based on the combustion of hydrocarbons, but other means of energy generation and storage like hydrogen fuel cells and corresponding hydrogen storage systems. The use of hydrogen as a primary energy carrier in aircraft poses novel and different hazards when compared to conventional propulsion and fuel storage systems. The study described in the present paper identifies, analyzes, and evaluates failure conditions and corresponding hazards that are associated with the electrified propulsion systems. Mitigation strategies to prevent failures to occur or decrease their severity are recommended. The effects of the assessed failures on aircraft, crew, and occupants are classified as catastrophic, hazardous or major as defined in the according Certification Specifications. Failure Conditions occurring at the aircraft, system, and subsystem levels are considered and their effect on the aircraft and propulsion system is assessed. The hazards identified mostly emerge due to the properties of the gaseous or liquid hydrogen. They include the flammability of gaseous hydrogen and the very low temperatures of cryogenic liquid hydrogen as well as the installation of high voltage power infrastructure and high capacity heat exchangers.

Keywords Electric propulsion system · Failure condition · Functional hazard assessment · Cryogenic Hydrogen · Malfunction · Safety analysis

Abbreviations

EPS	Electric propulsion system
HFS	Hydrogen fuel system
BoP	Balance of plant
ARP	Aerospace recommended practice
AIR	Aerospace information report
CS	Certification specification
AMC	Acceptable means of compliance
SysML	Systems modeling language
IBD	Internal block diagram
EPT	Electrical powertrain
FCS	Fuel cell system
AS	Air system
TMS	Thermal management system
FFLZ	Flammable fluid leakage zone

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1 Introduction

With the emission of greenhouse gases and other pollutants, the growing aviation sector significantly contributes to climate change. In order to pave the way for a climate compatible aviation sector and comply to the goals of the "Flightpath 2050" policy set by the European Commission [1], the use of green hydrogen as an energy carrier and hydrogen fuel cells as a means of energy conversion is widely discussed. To implement the goals, several different concepts for novel propulsion systems and aircraft are being developed by companies and research institutes around the world. Hydrogen fuel cells do not rely on the combustion of fossil hydrocarbons like kerosene for energy conversion but use an electrochemical reaction of hydrogen and oxygen to generate electricity. In propulsion systems, the generated electricity is converted into mechanical power by electric motors. The mechanical power is then converted into propulsive power by a propeller or ducted fan. For continuous safe operation, a fuel cell requires additional systems that, for example, precondition operating media or ensure the fitting operating temperatures of the individual subsystems. These subsystems ensure a balanced operation of the fuel cell and are therefore called Balance of Plant (BoP) subsystems. To provide a safe and reliable operation, every newly developed or altered propulsion system or aircraft is mandated to undergo thorough safety assessments and reach regulatory safety goals. The processes of safety assessments and system development in the aerospace sector—proposed by the ARP 4761A [2] and the ARP 4754B [3] respectively—are integrally connected with each other and shall therefore not be conducted separately. Safety assessments of aircraft that use hydrogen as a primary energy carrier and their subsystems have been previously conducted in some studies. They mostly focus on the the novel hazards that emerge due to the properties of (liquid) hydrogen. In 1983, Brewer investigated the general safety of hydrogen-fueled aircraft that directly combust hydrogen in gas turbines [4]. The focal point of the investigation was on the properties of hydrogen. It was concluded that hydrogen-fueled engines would pose a lower risk to people in and the surroundings of the aircraft compared to engines combusting fossil hydrocarbons. Albeit further safety assessments and validating experiments are necessary to reach complete and final conclusions. Sefain developed an unconventional aircraft design that uses liquid hydrogen as a fuel and assessed some of the arising hazards [5]. The safety implications which the use and storage of liquid hydrogen have on the overall aircraft and ground handling are evaluated but safety aspects on the level of the propulsion system were not considered. It was concluded that if no hydrogen is released and ignited, no accidents are caused. The prevention of accidental hydrogen release and the avoiding of ignition sources is of importance. Several hazards associated with the use of hydrogen in aircraft are stated in a study by Adler and Martins [6]. Like the study presented in [4], they come to the conclusion that hydrogen itself has safety benefits over kerosene. Notable are the rapid evaporation and dispersion rates of hydrogen in the surrounding atmosphere preventing the pooling of liquid fuel. If hydrogen is ignited in unconfined spaces, the fire is likely very brief compared to a kerosene fire and the surrounding structures would not heat up to the point of total loss of structural integrity [4].

Kazula et al. provide an overview of functional failures that might occur in hydrogen fuel cell systems and associated systems [7]. In contrast, Liverani follows a more holistic approach by conducting a comprehensive system design and partial safety assessment process of a Fuel Cell System and the corresponding BoP systems [8]. Despite their different level of rigor, both works indicate that the use of liquid cryogenic hydrogen and high power batteries poses significant safety challenges. Liverani assesses some failure conditions occurring in airborne Fuel Cell, Thermal Management and Energy Storage Systems that are similar to the ones portrayed in the current work. In addition, corresponding operational means of mitigation for the assessed failure conditions are elaborated.

Several studies discuss the safety challenges that arise from the use of cryogenic hydrogen in general and in aircraft particularly. In a technical memorandum, Mital et al. mention several key challenges of which the cryogenic temperature, the permeation of outgassing hydrogen, hydrogen embrittlement and increased safety factors in storage vessels are relevant in the context of this work [9]. If the piping and tanks carrying cryogenic liquids are not adequately insulated, the cold temperatures transfer to the outer surfaces and any surrounding gas, apart from helium, can solidify and thereby cause new hazards. To minimize heat transfer and therefore prevent cryogenic temperatures on outer surfaces as well as the permeation of gaseous hydrogen, passive and active insulation approaches can be employed and are further explored subsequently. Yin et al. review the recent progress in storage solutions and describe conventional as well as novel insulation approaches [10]. Conventional approaches reach from stacked insulation, where low conductivity materials are wrapped around piping and tanks, to multi-layer insulation (MLI), where multiple layers of different materials that reflect radiation minimize the overall heat transfer. The novel approaches improve the conventional approaches by utilizing novel materials in the multi-layer insulation (MLI) and combine it with different grades of vacuum making them so-called vacuum multi-layer insulations (VMLI). According to [10], novel insulation methods can introduce *hollow glass microspheres (HGM)*, *aerogel blankets* or *fibre reinforced plastics (FRP)* into VMLIs. The introduction of a vapor cooled shield (VCS) into the previously mentioned (V)MLIs as an active insulation method is also discussed. Excess evaporated hydrogen from the tank is led through the layers, creating a cooling shield that leads to a minimized heat transfer through the wall and, therefore, to an improved insulation. The reduction or even prevention of heat transfer also has notable benefits in reducing the rate of hydrogen boil-off.[1] Most of the aforementioned insulation approaches are not specifically designed with aerospace applications in mind. Consequently, in [10], the mass of these systems only plays a secondary role. Aerospace applications, on the other hand, are very mass sensitive. Johnson et al. investigated the implementation of cryogenic hydrogen infrastructure into a single aisle aircraft [12]. They assessed HGM, aerogel blanket, high performance vacuum and further insulation methods and came to the conclusion that, for an aircraft application, a high performance vacuum jacketed tank is the most sensible option regarding the trade-off between system mass and heat transfer rate and therefore losses due to boil-off. In addition to thermal insulation, hydrogen permeation through

[1] "Continuous but slow evaporation of liquefied gas" [11, p.5].

walls is another relevant factor when designing insulation for hydrogen infrastructure. Like the heat transfer, the permeation can be limited by introducing additional means of insulation. According to [6], a liner designed specifically to prevent permeation can be implemented into an MLI. This approach contrasts with more recent work by Boeing [13]. They developed a composite tank design for spacecraft that works without a liner, demonstrating potential advances in permeation-resistant materials. Different metallic materials have different susceptibilities to hydrogen embrittlement at different temperatures (the risk of embrittlement rises with a decreasing temperature). Steel, for example, has a high susceptibility, whereas aluminum has a low susceptibility and is therefore preferred especially in gaseous hydrogen applications [6]. In general, the management of cryogenic hydrogen brings many uncertainties that make an increased safety factor necessary. Adler et al. and Johnson et al. mention an increased safety factor for pressurized hydrogen vessels of 1.5 and 2.25, respectively [6, 12].

According to Calabrese et al. the accumulation of hydrogen in confined spaces following a leak or excessive permeation poses a significant safety risk [14]. In order to mitigate this risk, it is necessary to develop and implement reliable hydrogen sensing technologies that are able to detect gaseous hydrogen concentrations in confined spaces. Jha et al. explore one approach of periodic hydrogen sensing [15]. A network of sensors spanning the areas of the aircraft that contain hydrogen is developed and first tests are conducted. They focus on the design of the network and mention the use of *micro-electromechanical systems (MEMS) sensors*. Other sensor technologies for detecting hydrogen concentrations include fiber optic sensors, metal oxide sensors, catalytic gas sensors and ultrasonic sensors [16]. Franke et al. investigate the design of novel hydrogen sensing technology for aircraft [17]. Their research focuses on a sensor type that works based on the changing properties of metal hydrides upon contact with hydrogen. They studied several sensors and evaluated them based on their performance, their operational safety and other relevant criteria. Several organizations publish standards on hydrogen concentration sensing, that are not necessarily intended for the sensor design and placement in aircraft. Calabrese et al. summarize these standards, which include those issued by the *European Committee for Electrotechnical Standardization* and the *International Organization for Standardization (ISO)* [14, p.12]. The Aerospace Information Report *AIR6464*, published by the Society of Automotive Engineers (SAE), provides guidance on safety considerations of hydrogen fuel cells used in aircraft [18]. The AIR mentions several methods for preventing hydrogen fires. For example, the document recommends forced ventilation of confined spaces upon detection of a hydrogen leak, as well as the use of shutoff valves downstream of the tank to isolate potential leaks.

The intention of this work is to investigate a novel propulsion system of a regional airliner and to highlight some of the potentially frequently emerging safety challenges associated with the electrification of propulsion systems and the use of cryogenic hydrogen as a primary energy carrier. To discuss the safety challenges, failure conditions on aircraft, system or lower levels are assessed and their potential effects on the aircraft and the propulsion system are described.

Compared to existing research in the field, such as [8], the current paper presents a novel approach that identifies individual failure conditions likely to occur in electrified propulsion systems that use cryogenic hydrogen as a primary energy carrier. In contrast to the holistic assessment process conducted in [8], this approach focuses on specific failure conditions rather than evaluating the entire propulsion system. The hierarchy of system levels is disregarded here, and assessed failure conditions can occur at any level of the propulsion system. Furthermore, detailed operational and technical mitigation strategies are presented for selected failure conditions.

2 Methodology

A general safety process for the assessment of *Civil Aircraft, Systems, and Equipment* is suggested by the Aerospace Recommended Practice - ARP 4761A [2, p. 18–19]. Within the ARP 4761A, several assessment processes are proposed that assess various aspects of the system safety on different system levels. The general safety process includes all of the proposed assessments and can be adapted according to the needs of the safety engineer. Individual assessments can be omitted or added as required. Within this work, no thorough assessment is conducted but single individual failure conditions that can be the result of any assessment are analyzed. A failure condition is defined as *"a condition having an effect on the aeroplane and/or its occupants, either direct or consequential, which is caused or contributed to by one or more failures or errors […]."* in CS 25.1309(5)(q) [19, p. 837]. To analyze specific failure conditions and to get an understanding of the broad logical system architecture, the systems level structure and the media flows, an exemplary abstract system architecture is defined. The system architecture is shown using an adapted and simplified Internal Blockdiagram (IBD), that is based on the notation of the Systems Modeling Language (SysML). The diagram shows information about the detailed composition of relevant objects in a system (eg. subsystems) and associated object flows (e.g. information flows). The definition of the logical system architecture is based on previous and ongoing research projects and is meant to give a broad overview of what systems, subsystems and components are in the scope of the safety assessment of this work.

A literature study and research of any possible failures or errors in the defined systems, subsystems and components is conducted and ongoing project work is analyzed. In addition, the knowledge of experts on the respective systems is consulted to gain a deeper understanding of the mechanisms leading to the failures. The identified individual failure conditions and the underlying hazards are evaluated and classified, according to the corresponding regulations. The classification is based on the CS 25.1309 [19, p.840ff] and only failure conditions that have a severe classification—*Catastrophic*, *Hazardous* and *Major*—are considered and documented. According to the CS 25 and the ARP 4761A, the definition of failure conditions is followed by the allocation of effects the condition has on the aircraft, the occupants excluding the flight crew and the flight crew itself. Although all three kinds of effects are shown in Table 1, this work considers the effect that leads to the most severe classification of the respective failure condition (e.g. *Catastrophic*). The focus of this work shall not be on the methodology of the safety processes themselves but on the failure conditions and their effects. Hence only the findings of previously performed safety assessments are analyzed and discussed. The assessed failure conditions can originate on lower level systems and the worst case—their propagation to the Electric Propulsion System (EPS) and Aircraft levels is assumed to allow for a classification of the effects according to Table 1. The classifications are justified by qualitative assumptions relying on engineering judgement of the safety engineers. Other, more in depth methods of justification like simulation and laboratory as well as flight test as recommended in the ARP 4761A [2, p. 46], are not in the scope of this work.

After the failure conditions have been identified and classified, measures are proposed that could mitigate the severity of a single failure condition or prevent its occurrence. The failure conditions, the effects, the classifications and the proposed mitigation measures are documented in a table. It does not represent a specific assessment as per ARP 4761A but is a collection of safety issues to take into consideration when designing an electrified propulsion system. A quantitative assessment of any kind is deliberately not made within this work in order to ensure a general validity and comparability.

3 System definition

The assessed system is a propulsion system concept for a regional all electric aircraft with the following top level operational parameters.

- Design range 1000 NM
- Flight altitude 27000 ft
- Cruise speed Ma 0.55
- Passengers 70

The aircraft has ten nacelle integrated propulsion systems that are distributed over the wingspan of both wings of the aircraft (Distributed Propulsion). Every subsystem of any EPS is located within a respective nacelle as portrayed in Fig. 1. The aircraft architecture with the distributed propulsion approach as well as its depiction are those published by Sain et al. [20], which includes the top level operational parameters, the overall aircraft configuration and the number of intended EPS. Any lower level system architecture of the EPS and its subsystems that is assessed here, was developed for the purposes of this research. The Hydrogen Fuel System (HFS) is included in the scope of this work although it is not a part of the EPS. It is contextualized as a context-specific interface system (*actor* according to the SysML) of the EPS. A large section of the HFS—the liquid hydrogen tank (LH2 Tank)—is located in the aft section of the fuselage. The auxiliary hydrogen systems have the function of transporting hydrogen to the EPS and are therefore located throughout the aircraft in between the hydrogen storage and the EPS. The power output of each EPS can be individually controlled—autonomously or manually—if necessary, so a potential irregular asymmetric thrust can be compensated for. Figure 2 shows the IBD of the EPS and the HFS including the object flows, the system boundaries and a level structure. As

Table 1 Failure classification according to CS 25.1309 [19]

Classification of failure conditions	Severity of the effect		
	Effect on aeroplane	Effect on occupants excluding flight crew	Effect on flight crew
Major	Significant reduction in functional capabilities or safety margins	Physical distress, possibly including injuries	Physical discomfort or a significant increase in workload
Hazardous	Large reduction in functional capabilities or safety margins	Serious or fatal injury to a small number of passengers or cabin crew	Physical distress or excessive workload impairs ability to perform tasks
Catastrophic	Normally with hull loss	Multiple fatalities	Fatalities or incapacitation

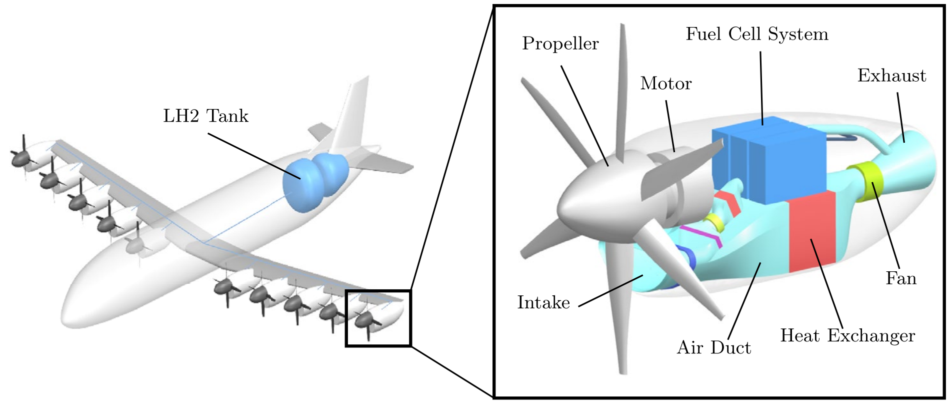

Fig. 1 Depiction of the aircraft with distributed propulsion and a single EPS, reprinted from [20] with permission from the author

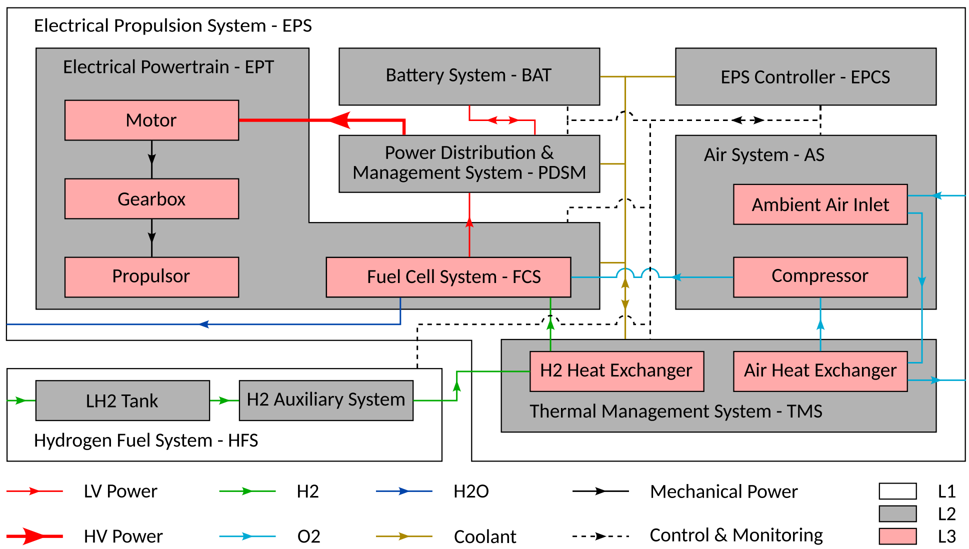

Fig. 2 Internal block diagram IBD of the EPS

level 1 systems (L1), the EPS and the HFS are subordinate to the Aircraft. They have several level 2 systems (L2) that in turn contain their specific level 3 systems (L3). Only a few L3 systems are depicted in Fig. 2 to describe the technical functionality of the EPS. Some of these L3 systems are in turn featured in the assessed failure conditions. Designing an exhaustive system model that includes every necessary L3 system is out of the scope of this work. All major power conversions take place in the central L2 system of the EPS, the Electrical Powertrain (EPT). It contains the Fuel Cell System (FCS) that converts chemical to electrical energy, the Motor that converts electrical to mechanical energy and the Propulsor that converts mechanical energy into thrust. Inputs of the EPT are the preconditioned operating media like gaseous hydrogen conditioned to the ideal operating temperature and pressurized air. The operating media are conditioned by the BoP systems that are located within the Air System (AS), the Thermal Management System (TMS) and the H2 auxiliary systems of the HFS. The FCS contains several individual interconnected fuel cells that use a set of electrochemical reactions to generate electrical energy.

Each individual fuel cell consists of two sides—the Anode and Cathode side which are separated by a Proton Exchange Membrane (PEM). Preconditioned gaseous hydrogen and preconditioned ambient air flow into the respective sides of the cell through gas diffusion layers towards the membrane. A catalyst on both sides of the membrane enables the respective reactions. The membrane only allows hydrogen protons to pass from the anode to the cathode side. The remaining electrodes pass through a load circuit to the cathode side and therefore represent the electrical output of the fuel cell. The reaction on the anode side of the cell produces water out of hydrogen protons and the oxygen contained in the conditioned ambient air. The reaction on the anode side is as the one on the cathode side, enabled by the installed catalyst layer [21]. The electrical output of the FCS is a Direct Current (DC) low voltage power that is transmitted to the Power Distribution & Management System (PDMS) where it is partially transformed into Alternating Current (AC) high voltage power by a set of converters and inverters. The AC high voltage power is then consumed by the Motor which is a three-phase synchronous machine with one transistor per phase. To store electrical energy and buffer the fluctuating power demands of the Motor, the EPS provides a Battery System (BAT). The BAT is comprised of a high energy lithium ion battery with several interconnected battery cells and corresponding battery management systems. The cooling of all L2 systems is provided by a coolant that dissipates heat in the central heat exchangers of the TMS (H2 Heat Exchanger and Air Heat Exchanger). The coolant provides a heat sink for the EPT, the PDMS, the BAT and the EPS Controller (EPSC).

4 Failure conditions

This section elucidates and analyzes selected failure conditions and their severity. Potential means of mitigation are proposed for the selected cases. All of the assessed failure conditions within this work are portrayed within the condensed Tables 2, 3 and 4. The tables are limited to the columns representing the failure conditions, the Effects of the failures and the according classifications. The complete collection of failure conditions of the system mentioned in Sect. 3 can be found in the appendix. It includes additional information about the proposed means of mitigation for every identified failure condition.

4.1 General

As described in Section 3, the aircraft concept has several propulsion systems that are equally distributed along each wing (refer to Fig. 1). In case of a total loss of one single EPS - OEI[2] (e.g. FC08 in Table 3), the aircraft shall still be able to perform a continued safe flight and landing [19, p.376]. The high level of redundancy provided by the fact that ten EPS are installed on the aircraft, can be a means to comply with that requirement. Additional redundancies within the subsystems and components that are installed in the nacelles, are not necessary. The total loss of one EPS does generally not lead to a catastrophic failure condition. The only risk for a single point of catastrophic failure of multiple EPS is posed by the HFS. According to CS 25.1309(b)(1)(ii) [19, p.832] a catastrophic failure condition shall not result from a single failure. Hence the risk needs to be mitigated and the HFS is to be equipped with appropriate redundancies. That implies that two independent LH2 Tanks and H2 Auxiliary Systems with the ability of cross feeding into each other should be provided. In addition the individual HFS components need to provide a high reliability. A diversification of subsystems and components throughout all installed EPS should be implemented to prevent the loss of multiple

[2] OEI - One Engine Inoperative.

Table 2 Failure conditions classified as catastrophic

ID	Failure condition	Failure effect (on aircraft, occupants excluding flight crew, flight crew)	Classification	Source
FC01	Accumulation of hydrogen in enclosed compartments above the lower flammability limit	High risk of fire and explosion leading to a large reduction in functional capabilities and safety margins possibly with hull loss	Catastrophic	[22]
FC02	Hydrogen embrittlement of structural parts of the aircraft due to exposition to gaseous hydrogen	Loss of structural integrity and disintegration under high mechanical stresses resulting in hull loss	Catastrophic	[23, 24]
FC03	Liquefaction of ambient oxygen on cryogenic surfaces, such as the walls of liquid hydrogen pipes or tanks	High risk of fire and explosion if liquid oxygen comes into contact with any organic material or oil/grease leading to a large reduction in functional capabilities and safety margins possibly with hull loss	Catastrophic	[25]
FC04	Disintegration of the outrunner rotor in flight segment with a high RPM value	Total loss of propulsion system and risk of damage of surrounding critical Systems and Components resulting in a large reduction of functional capabilities and safety margins with possible fatalities due to high energy debris	Catastrophic	[19]
FC05	Full thermal Runaway occurring in the Battery System due to improper thermal conditioning and subsequent heat accumulation leading to a sudden total loss of power provision and causing a rapid thermal expansion	Total loss of single propulsion system and an explosion resulting in fire in the battery compartment possibly leading to a hull loss	Catastrophic	[26]

Table 3 Failure conditions classified as hazardous

ID	Failure condition	Failure effect (on aircraft, occupants excluding flight crew, flight crew)	Classification	Source
FC06	Partial blockage of Heat Exchanger inlet ducts by frozen matter in icing conditions	Partial loss of cooling capacity resulting in an overheating FCS and subsequent accelerated membrane drying and possibly membrane deformation leading to a large reduction in functional capabilities and safety margins of the EPS	Hazardous	[31]
FC07	Total failure of the main shaft leading to a total loss of propulsive power generation and a sudden loss of torque	Total loss of rotational resistance leading to a sudden steep increase of RPM of the Motor and the total loss of propulsion system leads to a large reduction in functional capabilities and safety margins of the Aircraft	Hazardous	[32]
FC08	Short circuit in high voltage power electronics (inverters) due to overheating	Total loss of inverter leading to total loss of propulsion system resulting in a large reduction of functional capabilities of the Aircraft	Hazardous	[33]
FC09	Gap in an AC high voltage conductor located in a Flammable Fluid Leakage Zone (FFLZ) leading to a total loss of power transmission and possibly arcing	Total loss of propulsion system and an increased risk of fire and explosion with ignitable gases present leading to large reduction of safety margins of the Aircraft	Hazardous	[34]
FC10	Overheating and subsequent irreversible demagnetization of magnets in the PM Motor	At least significant to total loss of mechanical power output of motor leading to a large reduction in functional capabilities and safety margins of the Aircraft	Hazardous	[35]
FC11	Total loss of power generation due to freezing of the moist PEM in adverse operating conditions	Total loss of restarting capabilities of propulsion system leading to a large reduction of safety margins of the Aircraft	Hazardous	[36]
FC12	Thermal Runaway occurring in the Battery System due to improper thermal conditioning and subsequent heat accumulation leading to a sudden partial loss of power provision and the emission of highly flammable gases	Partial loss of propulsion system and a presence of flammable gases within the battery compartment lead to a large reduction in safety margins and functional capabilities of the Aircraft	Hazardous	[26]

Table 4 Failure conditions classified as major

ID	Failure condition	Failure effect (on aircraft, occupants excluding flight crew, flight crew)	Classification	Source
FC13	Fouling of heat exchanger pipes conducting any liquid leading to a partial loss of heat transfer and an increased pressure drop	Significant decrease of cooling capacity and subsequent high risk of damage to the FCS and other systems due to overheating leading to a significant reduction in functional capabilities of the EPS	Major	[37]
FC14	Partial loss of power generation due to the membranes of the PEM FC drying out	Increased degradation of membranes and insufficient power supply for the propulsion system resulting in a significant reduction in functional capabilities and safety margins of the EPS	Major	[36]
FC15	Ingestion of foreign matter into the compressor leading to a partial loss of the conditioned air massflow to the FCS	Solid particle erosion in ducting systems and the Compressor leading to a decreased efficiency and subsequent loss of function and thus a significant reduction in functional capabilities and safety margins of the EPS	Major	[38]
FC16	Ingestion of airborne contaminant into the FCS leading to a poisoning of the fuel cell	Poisoning of Fuel Cell leading to a decline in energy output and a significant reduction in functional capabilities and safety margins of the EPS	Major	[39]
FC17	Undetected excessive ambient air massflow into the FCS leading to a low air utilisation and subsequent drying out of the membrane	Increased degradation of membranes and insufficient power supply for the propulsion system resulting in a significant reduction in functional capabilities and safety margins	Major	[36]

EPS due to identical failures occurring at the same time in multiple EPS.

4.2 Failure conditions with catastrophic classifications

Three out of five catastrophic failure conditions listed within Table 2 arise due to the presence of hydrogen in any state of matter. It becomes apparent that the use of hydrogen as a primary energy carrier in general poses a significant risk factor for the safe operation of the aircraft. The cases with the IDs *FC01* and *FC02* are analyzed in more detail. In both cases the failure condition leads to multiple fatalities and a loss of the aircraft in a worst case scenario. According to Table 1 a failure condition with the aforementioned effects is to be classified as catastrophic. The occurrence of catastrophic failure conditions shall be *extremely improbable*[3] and they are "not anticipated to occur during the entire operational life of all aeroplanes of one type" according to CS 25.1309(7)(b)(4) [19, p.841].

Failure Case *FC01* describes an accumulation of gaseous hydrogen within any enclosed compartment anywhere in the aircraft. In this case the hydrogen concentration within the compartment increases above the lower flammability limit of hydrogen in the air. The lower flammability limit is reached at a hydrogen concentration of 4 vol% whereas the lower detonation limit is reached at a concentration of 18.6 vol% [27]. Hence the risk of fire and the risk of explosion can be evaluated separately. However, as any flammable concentration of hydrogen is not allowed in any compartment except for the intended, fire and explosion risks are assessed within a single failure condition. The CS 25.1181 assigns Designated Fire Zones for a number of compartments within or near the fuel burning power plant [19, p.761]. Similar to the CS, in the current work every zone or compartment within the aircraft that entails ducting containing hydrogen or any other flammable fluid is designated as a Flammable Fluid Leakage Zone (FFLZ). The worst case would expect that a sort of ignition source and a concentration of gaseous hydrogen above the lower flammability limit are present within the respective FFLZ. An ignition source could be a gap in any conductor possibly leading to arcing (compare *FC09* in Table 3). The CS 25.863 and the according Acceptable Means of Compliance (AMC) [19, p. 575] require means of risk reduction like ventilation and monitoring of the designated fire zones, among other means. To mitigate the effects of the failure condition of *FC01*, each FFLZ shall be either permanently ventilated or permanently monitored for its hydrogen concentration with a forced ventilation triggered when the concentration of hydrogen reaches a value just below the lower flammability limit to allow for a safety margin. Standards like ISO 26142:2010, which define requirements for hydrogen detection, can be consulted when designing FFLZ monitoring systems [28]. However, it is essential to note that ISO 26142:2010 is intended for the use of hydrogen detection systems in stationary applications. Specific boundary conditions for the application in the aerospace domain, like strong vibration, extreme temperature and air density and others need to be considered when the standard is used as a certification basis for an aerospace application. If a hydrogen leakage occurs and any structural parts of the aircraft are exposed to gaseous hydrogen, a loss of the structural integrity of the respective part can be the result. Exposure to hydrogen can lead to embrittlement, subsequent microscopic cracking and ultimately degradation of any metallic materials [24]. In the worst case scenario, that degradation leads to a structural failure of the material. *FC02* assesses that case and the worst case of structural failure of any load carrying structure within the aircraft is assumed. Load carrying structures in aircraft are for example located within the root of the wing structure. If there is a deformation or even a structural failure occurring, multiple fatalities and a total loss of the aircraft can be the consequence. *FC02* is therefore classified as catastrophic. Ventilation of the surroundings of hydrogen-containing ducting (previously defined as FFLZ) can prevent components outside the FFLZ from being exposed to gaseous hydrogen. If the exposure is prevented the embrittlement and possible structural failure can be averted. In addition, different alterations of the micro-structure of the potentially affected metallic materials can lower the susceptibility of hydrogen embrittlement. Sun et al. mention methods such as *Grain Boundary Engineering* and grain refinement to reach a higher hydrogen tolerance [29]. According to Holbrook et al., further means of protecting metallic material from embrittlement are the coating of the structure with *hydrogen-permeation-resistant-coatings* or the use of other *surface-conservation techniques* [30].

4.3 Failure conditions with hazardous classifications

All failure conditions that are assessed and classified as hazardous, are specified within Table 3. Several hazardous failure conditions lead to a total loss of the main functionality—providing thrust—of the respective EPS (refer to Section 3). A failure within one of the inverters of the motor can render the motor and therefore the EPS inoperative. Case *FC08* describes a short circuit within an inverter that can occur due to thermal breakdowns leading to "very high local temperature spots" [33] and a subsequent loss of the individual inverter. To mitigate the effects of this failure condition two sets of windings can be installed within a single motor making it a dual three phase (2×3 phase) motor. Each winding is supplied by an individual inverter

[3] Extremely improbable - quantitative probability of 10^{-9} occurrences per flight hour.

leading to independent redundancies within the motor and inverter. In the event of a short circuit in one of the inverters or one side of a dual three phase motor, one part of the motor becomes inoperative, but the overall system can still produce approximately half of the maximum mechanical power of a fully functional motor-inverter combination. Demir and Aydin [40] and Wu et al. [41] have assessed the reliability and redundancy of dual three-phase motors and redundant inverters, respectively, and state the overall increased reliability and the achieved redundancy. The combination of phase redundant circuits and dual three phase motors leads to the aforementioned independent redundancy. In addition, the implementation of an effective and reliable thermal management of the inverters is required to prevent the occurrence of short circuits due to local thermal breakdowns as discussed by Wu et al. [41]. If the thermal conditioning of any installed high energy lithium ion battery[4] malfunctions as described in *FC12*, an accumulation of heat can lead to a thermal runaway and a subsequent partial loss of the EPS. The consequences of thermal runaway of lithium ion batteries are a rapidly rising temperature and the emission of mixed, highly flammable gases. With an ever rising temperature and expansion of the battery cells, subsequent combustion and explosions are likely to occur within and outside of the cells [26]. The case *FC12* only assesses the partial loss of propulsion and the emission of flammable gases. Its effect on the aircraft is therefore classified as hazardous. The combustion and explosions that occur in the further course of the process of thermal runaway are classified as catastrophic within *FC 05*. To prevent thermal runaway, a precise and redundant monitoring of the thermal behavior and an accurate and reliable thermal management are necessary. The thermal management enables the battery temperature to be kept within the ideal operating range. These mitigation approaches correspond to the requirements for storage batteries in the CS 25.1353, where a "safe cell temperature" [19, p.1010] is demanded. Any compartment containing high energy batteries and its immediate surroundings is designated as a FFLZ and must therefore be ventilated and equipped with respective fire detection and extinguishing features. According to CS 25.863 a fireproof[5] containment is required in areas where flammable fluids like highly flammable gases might occur to prevent fault propagation and mitigate the consequences of thermal runaway. Based on engineering judgement, additional means for lithium battery fire extinguishing shall be installed in said compartments like required in the CS-E: Each fire zone within the engine shall be equipped with fire extinguishing means [43]. Wang et al. discuss several further mitigation means for thermal runaway, including the modification of the used materials of electrodes, separators and electrolytes [26].

4.4 Failure conditions with major classifications

Many of the failure conditions that are classified as Major within Table 4 describe processes that lead to a premature degradation of components or subsystems like the FCS, the AS or the TMS. Premature degradation is a process that usually does not lead to acute severe failures but is an issue that happens over time and is initially recognized through a loss of performance. Premature degradation mostly leads to shorter maintenance intervals and resulting economical detriments. The ingestion of airborne contaminants from the ambient air can lead to a poisoning of the PEM fuel cell and a subsequent steadily increasing loss of electrical power output. *FC 16* (Table 4) assesses the case of contamination of the catalyst on the cathode side. Several different contaminants like sulfur oxides, nitrogen oxides and others can negatively affect the functionality of the catalyst and interfere with the intended reaction. The composition of the ambient air and thus the occurrence of contaminants can vary depending on the flight mission (altitude, geographic location). Different solutions can be implemented to prevent premature degradation due to poisoning. Novel catalysts that are tolerant to some pollutants, ozone treatments and filtration of the airflow are means of mitigation to at least partially prevent the premature degradation of the catalyst due to airborne contaminants according to Shabani et al. [39]. Similar to the degradation due to poisoning, the operation of a fuel cell with a membrane that is too dry leads to an accelerated degradation of the cell. If the degradation is not detected and appropriate measures are taken, the consequence is a steadily increasing loss of electrical power output that can eventually culminate in a total loss of electrical power output of the individual cell if no mitigative actions are taken. In case *FC 14* (Table 4) only the partial loss of electrical power output is assessed. The dryness of the membrane leads to an increase in the ohmic voltage losses and thus to a decrease of the output voltage over time. The output voltage and current directly determine the aforementioned electrical power output of the fuel cell [21]. To prevent the cells from drying out, a redundant monitoring of the humidity and a reliable humidification of the ambient air entering the cell shall be implemented. The influence of an altered humidity on the temperature range of the airflow entering the cathode side of the fuel cell stack needs to be considered when integrating the means of humidification. Furthermore, according to Vidović et al., a humidifier is one of the BoP systems that needs to be implemented to constantly maintain the ideal humidity of the cathode air [44].

[4] the term High Energy Battery, e.g. High Energy Lithium Ion Battery - HE-LIB, refers to Batteries with energy densities in the order of 400 Wh kg^{-1} [26].

[5] Fireproof: "Equipment installed in fire zones which must function during the first five minutes of fire and which must keep its safety functions for at least fifteen minutes" DO-160 26.3 [42, p.26-1].

5 Conclusion and outlook

The introduction of electrified aero engines and cryogenic hydrogen into the aviation sector poses several novel hazards for aircraft and their operation that can lead to failures with severe outcomes. The intention of the current study is to identify and highlight individual, critical failure conditions, rather than conducting a comprehensive safety process. An established system model serves as the basis for the subsequent safety assessments. The safety assessments focus on the identification of failure conditions and their classification. The failure conditions are identified by studying the corresponding literature, assessing ongoing project work and consulting experts on the relevant systems. To evaluate the single failure conditions, the classification is conducted according to the CS 25.1309 [19]. A majority of the failure conditions herein classified as catastrophic is caused by the properties of the carried cryogenic hydrogen. The flammability of hydrogen gas and the very low temperature of liquid hydrogen can pose severe hazards for the systems containing the fuel. Some failure conditions leading to the total loss of a single electric propulsion system are classified as hazardous, because the high number of installed propulsion systems within the aircraft provides high redundancies. A loss of a single electric propulsion system can be compensated for by the remaining systems. However, the loss can still lead to a large reduction in functional capabilities and safety margins and is hence classified as hazardous according to Table 1. Unlike with the electric propulsion system, a redundancy is not inherent to the installation of the hydrogen fuel system, which needs to be taken into account when designing and integrating the electric propulsion system and the hydrogen fuel system into the aircraft. A total loss of the fuel system without corresponding redundancies would yield a catastrophic failure condition. For every assessed failure condition, one or more mitigation strategies are proposed. Zones or compartments entailing ducting containing hydrogen or any other flammable fluid are defined as flammable fluid leakage zones inspired by the Designated Fire Zones that are defined in Certification Specifications like the CS-25 [19]. One exemplary mitigation strategy for increased fire and explosion risk due to an accumulation of gaseous hydrogen in a confined space within the aircraft's system boundaries is the forced ventilation of the flammable fluid leakage zones. This ventilation is triggered in case the concentration rises above a defined limit that is below the flammability limit of hydrogen. Another failure condition whose effects can be mitigated using ventilation is the hydrogen embrittlement of metallic materials - mostly load bearing structures. Besides ventilation of the affected areas, methods like the alteration of the metals micro structure and a coating of the structures are possible.

The current paper offers an additional perspective on a variety of specific failure mechanisms that can occur anywhere in electrified propulsion systems, including the cryogenic hydrogen storage system, regardless of the system level. Instead of examining every detail of the aircraft and propulsion system by following the ARP4754B and ARP4761A design and safety assessment processes, this is achieved by focusing on the individual failure conditions. The proposed mitigation strategies are not only operational, but also functional. Design measures that shall be implemented to mitigate the negative effects of the failure conditions on the aircraft. When implementing standards and mitigation strategies, it needs to be considered that some of the mentioned means and standards have not been specifically designed for the use in aerospace applications. Like mentioned in Sect. 4.2, aerospace applications have a different set of boundary conditions compared to automotive or ground based stationary applications. In the weight sensitive aircraft domain, the trade off between additional weight—due to any additional safety system—and the aircraft's performance needs to be considered. The existing aerospace regulations do not yet provide a basis for a sufficiently thorough assessment (and certainly not a certification) of electrified propulsion systems with regard to their safety and failure scenarios. There are similarly few studies and papers on safety issues in electrified propulsion systems for aircraft in combination with cryogenic hydrogen—this study attempts to be a step in this respect. In comparison to a conventional propulsion approach using a gas turbine burning kerosene as a primary means of energy conversion, the hazards and risks emerging in the hydrogen fueled electric propulsion system are of a very different nature, with only a limited overlap. This necessitates to thoroughly rethink the emerging risks and hazards, the possible failure conditions, and their corresponding effects on occupants and the aircraft. The work described in the current paper contributes to this process of rethinking by providing a listing of exemplary failure conditions with different classifications. Furthermore, this listing requires expansion and further development to gain a deeper understanding of the failure mechanisms, their effects as well as to build a deeper understanding of the interrelations different failures and systems of different levels have. However, this work clarifies that some of the novel challenges in terms of safety may be overcome by implementing the portrayed functional or organizational mitigation strategies into the systems. As soon as any novel aircraft using an electric propulsion system goes into development, thorough assessments as per ARP 4761A [2] are essential and need to be thoroughly conducted.

Appendix

A.1. Failure conditions

See Table 5.

Table 5 Failure modes and effect analysis

ID	System	Failure condition	Failure effect (on A/C, crew, passengers)	Classification	Proposed mitigation	Sources
FC01	Aircraft	Accumulation of hydrogen in enclosed compartments above the lower flammability limit (4%) of hydrogen	High risk of fire and explosion leading to a large reduction in functional capabilities and safety margins possibly with hull loss	Catastrophic	Assignment of FFLZ (Flammable Fluid Leakage Zones) and monitoring and ventilation of these Zones	[19, 22]
FC02	Aircraft	Hydrogen embrittlement of structural parts of the aircraft due to exposition to gaseous hydrogen	Loss of structural integrity and disintegration under high stresses resulting in hull loss	Catastrophic	Ventilation of FFLZ, alter micro structures of metals, coat structures	[24, 29, 30]
FC03	HFS	Liquefaction of ambient oxygen on cryogenic surfaces, such as the walls of liquid hydrogen pipes or tanks	High risk of fire and explosion if Liquid Oxygen comes into contact with any organic material or oil/grease leading to a large reduction in functional capabilities and safety margins possibly with hull loss	Catastrophic	Insulation of any LH2 containing vessel	[25]
FC04	Motor	Disintegration of the outrunner rotor in flight segment with a high RPM value	Total loss of propulsion unit and risk of damage of surrounding critical Systems and Components resulting in a large reduction of functional capabilities and safety margins with possible fatalities due to high energy debris	Catastrophic	Containment of Motor (Casing, Nacelle, etc..)	CS 25.1309 11(b)(1) [19]
FC05	BAT	Full thermal runaway occuring in the Battery System due to improper thermal conditioning and subsequent heat accumulation leading to a sudden total loss of power provision and causing a rapid thermal expansion	Total loss of single propulsion unit and an explosion resulting fire in the battery compartment possibly leading to a hull loss	Catastrophic	Monitor thermal conditioning of the Battery and divide it into fireproof compartments to prevent propagation of Thermal Runaway	[26]
FC06	AS/TMS	Partial blockage of Heat Exchanger inlet ducts by frozen matter in icing conditions	Partial loss of cooling capacity resulting in an overheating FCS and subsequent accelerated membrane drying and possibly membrane deformation leading to a large reduction in functional capabilities and safety margins of the EPS	Hazardous	Prevent ice accretion on any air inlet surface	[31, 45]
FC07	EPT	Total failure of the main shaft leading to a total loss of propulsive power generation and a sudden loss of torque	Total loss of rotational resistance leading to a sudden steep increase of RPM of the Motor and the total loss of propulsion unit leads to a large reduction in functional capabilities and safety margins of the Aircraft	Hazardous	Implement control system that immediately adapts the RPM output of the motor, shuts down the EPS and possibly mechanically breaks the shaft	[46]
FC08	EPT	Short circuit in high voltage power electronics (inverters) due to overheating	Total loss of inverter leading to total loss of propulsion unit resulting in a large reduction of functional capabilities of the Aircraft	Hazardous	Implement multiple winding systems with independent windings in Motor and individual inverters for each winding system. Implement an effective reliable thermal management	[33]
FC09	PDMS	Gap in an AC high voltage conductor located in a Flammable Fluid Leakage Zone (FFLZ) leading to a total loss of power transmission and possibly arcing	Total loss of propulsion unit and an increased risk of fire and explosion with ignitable gases present leading to large reduction of safety margins of the Aircraft	Hazardous	Redundancy in HV BUS systems. Prevent installation of any high voltage power transmission BUS within any FFLZ	[34]

Table 5 (continued)

ID	System	Failure condition	Failure effect (on A/C, crew, passengers)	Classification	Proposed mitigation	Sources
FC10	Motor	Overheating and subsequent irreversible demagnetization of magnets in the permanent magnet (PM) Motor	At least significant to total loss of mechanical power output of motor leading to a large reduction in functional capabilities and safety margins of the Aircraft	Hazardous	Implement reliable cooling mechanisms for Motor components	[35]
FC11	FCS	Total loss of power generation due to freezing of the moist PEM in adverse operating conditions	Total loss of restarting capabilities of propulsion unit leading to a large reduction of safety margins of the Aircraft	Hazardous	Implement redundancies and means for independent heating of the FCS	[36]
FC12	BAT	Thermal Runaway occuring in the Battery System due to improper thermal conditioning and subsequent heat accumulation leading to a sudden partial loss of power provision and the emission of highly flammable gases	Partial loss of propulsion unit and a presence of flammable gases within the battery compartment lead to a large reduction in safety margins and functional capabilities of the Aircraft	Hazardous	Monitor thermal conditioning of the Battery and assign the Battery compartment a FFLZ that is to be ventilated	[26]
FC13	TMS	Fouling of heat exchanger pipes conducting any liquid leading to a partial loss of heat transfer and an increased pressure drop	Significant decrease of cooling capacity and subsequent high risk of damage to the FCS and other systems due to overheating leading to a significant reduction in functional capabilities of the EPS	Major	Overdesign the crosssection or diameter of ducts or pipes to address the pressure drop and require regular cleanings of Heat Exchangers	[37]
FC14	FCS	Partial loss of power generation due to the membranes of the PEM FC drying out	Increased degradation of membranes and insufficient power supply for the propulsion unit resulting in a significant reduction in functional capabilities and safety margins of the EPS	Major	Implement means of appropriate and redundant humidification	[36]
FC15	AS	Ingestion of foreign matter into the compressor leading to a partial loss of the conditioned air mass flow to the FCS	Solid particle erosion in ducting systems and the Compressor leading to a decreased efficiency and subsequent loss of function and thus a significant reduction in functional capabilities and safety margins of the EPS	Major	Implement a particle separator into the airstream up stream of the compressor	[38]
FC16	AS /FCS	Ingestion of airborne contaminant into the FCS leading to a poisoning of the fuel cell	Poisoning of Fuel Cell leading to a decline in energy output and a significant reduction in functional capabilities and safety margins of the EPS	Major	Implement a filter, Ozone treatment or tolerant catalysts	[39]
FC17	EPSC	Undetected excessive ambient air massflow into the FCS leading to a low air utilisation and subsequent drying out of the membrane	Increased degradation of membranes and insufficient power supply for the propulsion unit resulting in a significant reduction in functional capabilities and safety margins	Major	Implement mass flow sensors and an according monitoring software with a high design assurance level	[36]

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Declarations

Conflict of interest The authors declare no conflict of interest.

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