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Identification and assessment of zonal hazards emerging in highly integrated Distributed Electrified Propulsion Systems in aviation

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The increasing complexity of modern aircraft systems and in particular, concepts of novel highly integrated and Distributed Electrified Hybrid Propulsion Systems (DEHPS), introduce a variety of novel safety challenges in comparison to conventional aircraft engines. Those legacy propulsion systems are designed to be compact with all subsystems of the system typically being located within the physical system boundaries of the engine nacelle. A high degree of integration of individual DEHPS subsystems into the aircraft architecture and the introduction of new technologies lead to novel hazards and an increased effort for the assessment of the system safety. This study identifies physical hazards associated with the integrated architecture of a specific hydrogen powered DEHPS. Particular attention is paid to the assessment of hazards whose effects can propagate across system and zonal boundaries, affecting adjacent subsystems throughout the aircraft. The identification and assessment of said hazards is based on the Zonal Safety Assessment (ZSA). The ZSA methodology is defined in the Aerospace Recommended Practice - ARP 4761A by the SAE International. The DEHPS under consideration consists of multiple propulsion units distributed along the wingspan of an electrified aircraft with fuselage-integrated energy storage and conversion systems. This architecture leads to a spatial separation and a placement of the DEHPS subsystems in several different aircraft zones. The identification and evaluation of hazards show, that the integration of novel DEHPS poses risks for the safety of adjacent novel and legacy systems, aircraft zones and subsequently the entire aircraft. Aiming at the certifiability of this and similar novel propulsion systems, means of mitigation of the assessed hazards and failure conditions are developed and can be considered for the definition of future design and installation requirements.

Keywords: Aircraft safety, Zonal Safety Assessment (ZSA), Physical hazard, Mitigation, Airworthiness, Hydrogen Electric Propulsion

1. Introduction

Innovative electric and hybrid-electric propulsion systems offer several environmental advantages over legacy aircraft engines like mentioned by Thonemann et al. (2024) and consequently minimize the negative climate impact of the entire aviation sector. To obtain a certification of the novel systems, their behavior must be thoroughly understood. For every aircraft and propulsion system that is to be operated within Europe, the certification process is governed by the European Union Aviation Safety Agency (EASA) as explained by Hinsch (2022). The EASA (2023) (Part 21) publishes a basic regulation that contains the Implementing Rules for the initial and continued Airworthiness. For legacy aircraft engines, the failure modes are well known due to the long history of usage. Consequently means of mitigation are standardized and documented in the form of certification requirements for engines in the CS E as well as the aircraft in the CS 25 published by EASA (2020) and EASA (2023) respectively. The requirements defined in the CS form the basis of the initial airworthiness. To ensure the safety of an aircraft, it is necessary to identify the inherent hazards and mitigate the resulting potential risks. In complex systems, negative interactions between subsystems or components must be systematically analyzed.

Several designs of aircraft utilizing DEHPS have been proposed. Eissele et al. (2023) suggest an architecture, based on the ATR 42 and the ATR 72 as reference aircraft. Further concepts for the integration of DEHPS where proposed by Waddington et al. (2023) and de Graaf et al. (2024). All of the mentioned aircraft concepts feature a passenger seating capacity of more than 19 or a maximum certified take-off mass of more than 8618 kg (19000 pounds). The CS 25 is therefore the relevant certification specification document. Other projects have also investigated non CS 25 aircraft configurations, such as NASA's X-57 project, which analyzed a battery powered aircraft design using a DEP (Distributed Electrified Propulsion) concept. Kushner et al. (2024) describe the X-57 project from the systems engineering point of view, with the validation of the design being a fundamental part. In this context, Kurt V. Papathakis et al. (2017) published a hazard list and describe safety design considerations for the X-57 project. Several investigations of hazards occurring in the subsystems of a novel DEHPS, have been conducted. One exemplary novel subsystem is the high voltage DC network. Rotgerink and Schippers (2025) show methods to model serial arcs in high voltage DC aircraft networks to analyze the behavior of this physical hazard. First experience from the use and development of fuel cell systems and hydrogen exist in the automotive field. Song et al. (2025) describe functional and physical hazards for automotive fuel cell systems. Leakage of hydrogen as one hazard inherent to a fuel cell system is quantified, regarding the respective probability. Means of mitigation are suggested, that are based on redundant component design. Tang et al. highlight the risk of ignition and detonation, whereas the *"[...] ignition ranges of hydrogen with air are 4–75% (vol. %), while the detonation ranges are 13–65% (vol. %)"* (Tang et al., 2020, P.31285). The risk of high energy debris due to an uncontained rotor failure in turbofan engines has already been extensively investigated by Rossmann (2020). The challenge of containing high energy rotating parts remains for the novel components when replacing turbofan engines by electric motors. Introducing batteries as a propulsion energy storage entity poses various physical hazards, including the critical Thermal Runaway (TR) state. According to Wang et al. (2023), TR can lead to thermal hazards, for which mitigation measures are proposed. Additionally, Somandepalli et al. (2014) describe combustion and explosion hazards of lithium ion batteries in case of TR, while Li et al. (2026) investigate the influence of aviation hydraulic oil on TR characteristics. Furthermore, TR can result in the dispersion of *"[...] toxic gases, posing poisoning hazards to crew and passengers"*(Hu et al., 2025, p.17), in addition to functional hazards and a performance decrease. The diverse, complex and new technologies employed in DEHPS introduce a range of potential novel hazards. The relationship between these hazards and the zonal effects on other systems have not yet been assessed for narrow body aircraft. Chen and Fielding (2018) developed a *"Preliminary Zonal Safety Analysis"* for the early design phase of advanced aircraft technologies. This document adapts the ZSA process, but its application is limited to the N3-X project's unique design and cannot necessarily be applied to other aircraft configurations. While the mentioned previous works have assessed various individual zonal safety aspects occurring in different aircraft configurations and propulsion systems, they have not addressed the zonal safety challenges associated with integrating DEHPS into legacy narrow body aircraft architectures. This paper contributes to the safe design of these future aircraft and their certifiability, by providing the foundation for installation- and design requirements, focusing on the zonal effects of the hazards inherent to the novel systems.

2. Methodology

The general safety process, as recommended by the ARP 4761A published by SAE International (2023), includes various safety assessments for *civil aircraft, systems, and equipment*, including the ZSA. The ZSA assesses the physical instal-

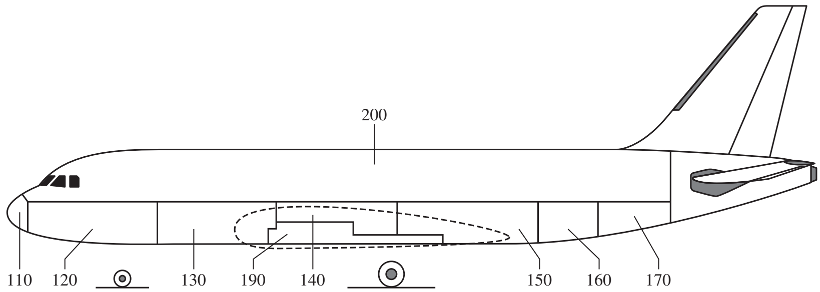

Fig. 1. Depiction of exemplary Zonal partition of aircraft (SAE International, 2023, p.261)

lation of entities[a] within a defined aircraft zone to identify hazards caused by proximity to other entities. A more detailed description of the ZSA process is documented in the ARP 4761A. It includes the necessary inputs as well as the aims of a comprehensive ZSA, conducted within the scope of a certification of an aircraft. The assessment conducted in this work is based on the ZSA process, adapted in a manner similar to the *Preliminary ZSA* process described by Chen and Fielding (2018). The methodology employed, is described in this section. Initially a system architecture, based on a comprehensive literature review is defined and described in section 3. The defined system architecture is subsequently partitioned into zones that are relevant for the assessment within this work. As a foundation for the zonal partitioning the proposed zonal structure from the ARP 4761A is taken as an example (see figure 1) and the zones 130, 140, 150 (lower Fuselage) and 400 (Nacelle) are identified as relevant. It is determined which DEHPS entities are located in each of the identified zones. In addition, the legacy airborne equipment that is also located in the respective zones is identified referring to Airbus S.A.S. (2002). Failure modes[b] are identified, and a collection of resulting entity-inherent physical hazards is established. Hazards that are posed by entities operating in their normal mode are also considered in that collection. The definition of the hazards is based on input of system experts and a continuative literature review. Hazards are subdivided into intra- and cross-zonal hazards. Intra-zonal hazards have effects that are confined to a single zone, whereas cross-zonal hazards have effects that transcend zonal boundaries as defined in SAE International (2023). Combining the entity-inherent hazards with the respective zone and the effect on entities within that zone or beyond, an intra- or cross-zonal safety item is developed. For each assessed safety item proper means of mitigation are determined based on an extensive literature review and well substantiated engineering judgement. This judgement is based on expert knowledge from system specialists and collaborative safety analysis sessions.

[a]Systems, subsystems and components are subsumed as ”entities” over the further course of this work

[b]”Failure Mode - Specific way in which a system, equipment, hardware item, or piece-part may fail”(SAE International, 2023, p.9)

3. System design

3.1. *General*

The assessed propulsion system is a DEHPS using liquid hydrogen as a primary energy carrier and a hydrogen fuel cell for energy conversion. The coarse DEHPS system architecture and subsystem placement assessed in this work, are based on architectures proposed by Waddington et al. (2023), de Graaf et al. (2024), and Eissele et al. (2023). These proposals are not fully adopted for this research and serve as a reference and inspiration for the architecture and entity placement. The assessed DEHPS comprises five core subsystems that are located in the fuselage:

(1) **Hydrogen Supply and Conditioning System - HSCS**: Manages cryogenic hydrogen, pressure regulation and thermal conditioning

to deliver gaseous hydrogen at the ideal operating parameters to the fuel cell stack.

(2) **Fuel Cell System - FCS**: Consists of redundant fuel cell stacks that convert hydrogen and oxygen into electrical energy and integrated cooling represented by heat exchangers.

(3) **Air System - AS**: Provides a conditioned airflow to the FCS while managing pressure, temperature and humidity levels using valves, heat exchangers and humidifiers.

(4) **Battery System - BAT**: Providing electrical energy storage and a buffer for the fluctuating power demands of the DEHPS.

(5) **Power Distribution and Management System - PDMS**: A distributed electrical network located throughout the aircraft that conditions and distributes propulsive electrical power across the DEHPS and provides the aircraft with electrical power.

And two subsystems located in each of the six nacelles, which are distributed across the wingspan of the aircraft:

(1) **Motor - M**: Converting electrical power into mechanical shaft power. Includes according power electronics like inverters.

(2) **Gearbox - GB**: Reducing the high RPM output of the motor into a suitable Propeller RPM.

Connections between the subsystems, such as power transmission lines, piping and any sort of monitoring and control data transmission lines, are considered part of both the subsystem they serve and the zone they traverse. Similar to the kerosene fuel tanks on conventionally powered aircraft, the hydrogen tank itself is not considered as a part of the DEHPS, but the system boundaries feature interfaces with the tank that transmit liquid hydrogen to the HSCS.

3.2. *Zonal Architecture and Distribution*

The DEHPS is distributed over four defined aircraft zones that are based on the example given by the ARP 4761A. The example of a zonal partition is shown in Figure 1. As a reference aircraft for the placement of legacy subsystems within the fuselage, the Airbus A320 is adopted and the aircraft manual of the A320 is used as a reference (Airbus S.A.S., 2002). It is to be noted that every zone located in the fuselage contains data and power transmission lines that are potentially safety critical for the operation of the aircraft.

The individual zones and their novel DEHPS and legacy entities are:

- **Zone 130 (forward fuselage)**: Contains the battery system positioned immediately forward of the wing root. The zone 130 interfaces directly with the zone 120 that comprises the avionics compartment.
- **Zone 140 (mid-fuselage)**: Contains the FCS and the AS as novel DEHPS systems and major parts of the Environmental Control System (ECS), the hydraulic compartment and the center wing box as legacy systems. Zone 140 neighbors both zone 130 (forward) and zone 150 (aft), creating cross-zonal interfaces for electrical power transmission, operating media flows and coolant loops.
- **Zone 150 (aft fuselage)**: Accommodates the HSCS and major parts of the power management and distribution system - PDMS, situated directly forward of the hydrogen tank. The zone contains piping that conducts Liquid Hydrogen (LH2) from the tank to the HSCS where it is distributed internally.
- **Zone 400 (nacelles)**: Each of the six wing-mounted nacelles contains a propulsion motor including the local power management components, and a gearbox. Unlike the zones located in the fuselage, zone 400 interfaces primarily with aerodynamic structures, with no direct cross-zonal coupling to zones 130 to 150.

Although the Hydrogen tank is not considered as a part of the DEHPS, it is a neighboring system of zone 150 and therefore of relevance for the assessment of cross-zonal effects. The partitioned aircraft is shown in figure 2 including the coarse distribution of the DEHPS subsystems and their connections and interfaces.

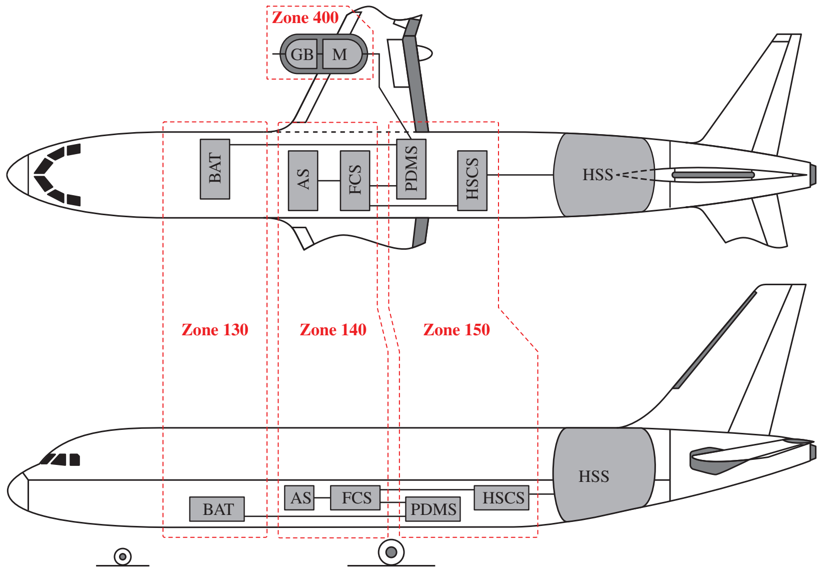

Fig. 2. Top- and side view of the aircraft with a coarse placement of integrated DEHPS-subsystems with the highlighted zones of interest

4. Results

The preliminary assessment of intra- and cross-zonal interactions due to DEHPS integration identified safety items and means of mitigation, with some of the results summarized in tables 1 and 2 and further discussed in the following paragraphs.

According to the mitigation of SI_01 the installation of more effective thermal insulation of piping as described by Fesmire and Swanger (2019), is recommended to minimize the temperature difference of the surface and the surrounding environment. This mitigation measure aims to reduce the risk of condensation of environmental humidity on cold piping that transfers cryogenic LH2 within pressurized and tempered compartments. This can lead to the formation of ice and water drops and potentially pose hazards for electric entities in zone 150 (Figure 2). Furthermore, a relocation of the according piping and therefore parts of the HSCS outside of the pressurized and tempered compartment should be considered to separate it from critical electrical components and minimize the extent of condensing water accumulation. An installation of the LH2 piping below the electric equipment with physical separation and adequate clearance from other entities in the zone is recommended to prevent moisture related hazards. The installation with adequate clearance is also suggested to prevent physical damage like chafing. This mitigation measure aims to reduce the risk of any structure transmitting vibrations and leading to potential chafing damage on entities like pipes or electrical lines in close proximity resulting in SI_02. The CS 25 lists several subsystem requirements (e.g. CS 25.967(a)(d); CS 25.1707(i)(1)) that aim to prevent hazards that occur due to chafing. Depending on the subsystem, means of mitigation like physical separation, but also the installation of pads are required. Especially any piping that transfers hydrogen is to be protected by separating it to prevent hydrogen leakages within the corresponding zones.

The zones containing any hydrogen infrastructure (140 and 150) are labeled as one Flammable Fluid Leakage Zone (FFLZ) like introduced in Rempe et al. (2025) in accordance with CS 25.863(d). To mitigate the fire and explosion hazards caused by an accumulation above the lower flammability limit of hydrogen in air (4%) as described by SI_07, an active or forced

Table 1. *

Intra-zonal safety items and corresponding mitigation

ID	Safety Item	Zones	Mitigation	Reference
SI_01	Water condensing on cold piping that conducts cryogenic LH2 due to a warm environment. Water forms drops and potentially drips on electric entities like the PDMS in zone 150.	150	Thermal insulation of piping, installation with according clearance	Fesmire and Swanger (2019)
SI_02	Stiff piping that can transmit vibrations leading to potential chafing damage on entities in close proximity.	130, 140, 150	Installation with according clearance; installation of pads to prevent damage	EASA (2023)
SI_03	Physical damage of entities in close proximity to HV power transmission line due to high temperature electric arc.	150, 400	Thermal shielding of HV power transmission lines, installation with according clearance	Rotgerink and Schippers (2025)
SI_04	Overheat of PDMS leading to an unintended very high temperature within the zone 150 as well as a shift of the dew point and subsequently potential condensing of water on cold surfaces.	150	Implement reliable and adjustable thermal monitoring and control of PDMS	Majid Asli et al. (2024)
SI_05	Debris with high kinetic energy from the rotor of the electric motor severing electrical power transmission lines in zone 400.	400	Containment of Motor to prevent uncontained rotor failures	Hou et al. (2022); Rossmann (2020)

Table 2. *

Cross-zonal safety items and corresponding mitigation

ID	Safety Item	Zones	Mitigation	Reference
SI_06	EMI of HV power transmission lines within zones 150, 400 and between affects electronic data handling entities leading to potential misinterpretations of data or control signals.	150, 400	Shielding of HV transmission lines, installation with according clearance	Lizcano et al. (2022)
SI_07	Accumulation of gaseous hydrogen above flammability limits (>4 vol%) with an ignition source present (arcing, friction sparks, high temperature surfaces)	140, 150	Forced/active ventilation of zone - assigning a FFLZ	Tang et al. (2020); DIN (2019) EN 1127-1
SI_08	Accumulation of gaseous hydrogen leading to degradation of structural integrity of parts (stringers, frames, wing box, etc) due to hydrogen embrittlement mechanisms	140, 150	Forced/active ventilation of zone - assigning a FFLZ; modification of structural metals	Song et al. (2025)
SI_09	Accumulation of flammable gases following TR of BAT with an ignition source present leading to an uncontrolled fire in zone 130	130	Forced/active ventilation of zone - assigning a FFLZ, containment of BAT	Somandepalli et al. (2014)
SI_10	Very high temperatures following TR of the BAT influencing forward avionics compartment (zone 120).	120, 130	Physical containment of BAT, active ventilation of zone	Wang et al. (2023)
SI_11	Accumulation of toxic gases in close proximity to the ECS leading to a distribution in major zone 200 (cabin).	130, 200	Redundant emergency cabin pressurization means to allow for forced ventilation	Hu et al. (2025)
SI_12	Accumulation of gaseous hydrogen in close proximity to the ECS leading to a distribution and concentration of above 4 vol% in major zone 200 (refer to figure 1) and a subsequent fire hazard.	140, 200	Redundant emergency cabin pressurization means to allow for forced cabin ventilation	Tang et al. (2020)

ventilation of the FFLZ is required. Additionally, fireproofing of any safety critical entity [c] located within the respective zone is required as per CS 25.1181. In addition, a constant and reliable monitoring of the hydrogen concentration in any FFLZ is required to provide cautions to flight crew and personnel. To prevent the further propagation of a potential hydrogen fire, the boundaries of any FFLZ shall withstand and contain fire. To prevent thermal damage and electromagnetic interference, thermal and electrical shielding of all installed High Voltage (HV) transmission lines is recommended. This mitigation measure aims to reduce the risk of Electromagnetic Interference (EMI) of HV power transmission lines within zones 150 and 400 (Figure2) as portrayed in SI_06. EMI can affect electronic data handling entities and lead to potential misinterpretations of any data or control signals. Additionally, the mitigation prevents thermal damage following the formation of a high temperature electric arc, as explained

[c]Entity whose failure prevents continued safe flight and landing.

by Rotgerink and Schippers (2025). The implementation of a reliable and adjustable thermal monitoring and control of PDMS is recommended to regulate the operating temperature and prevent overheating according to SI_04. An unintended very high temperature within zone 150 due to PDMS overheating leads to a shift of the dew point, resulting in potential condensing of water on cold surfaces and subsequent accumulation. This accumulation of liquid water in an area with critical electrical entities must be prevented, similar to the previously described condensation of environmental humidity.

According to Wang et al. (2023) the event of a TR of the BAT in zone 130 would yield very high temperatures and emit highly flammable and toxic gases as outlined by SI_09. To mitigate a cross-zonal effect on the forward avionics compartment, located in zone 120 (Figure 1), an according physical containment of the BAT and a forced ventilation of the zone are suggested. Due to parts of the Environmental Control Subsystem (ECS) being located in zones 130 and 140, the emission and dispersion of toxic and flammable gases following the TR event, potentially lead to a distribution of said gases into the major zone 200 and therefore the cabin as depicted in Figure 1. The previously suggested containment mitigates this hazard as well by reducing or preventing the accumulation of toxic and flammable gases in close proximity to the ECS as described in SI_11. A redundant and secluded emergency cabin pressurization system is recommended to prevent the toxic and flammable gases from spreading and potentially harming occupants or posing a fire hazard in zone 200. Debris with a very high kinetic energy due to a loss of structural integrity of a rotor in the electric motor or a shaft can sever HV power transmission lines in zone 400 (Figure 2). The failing mechanisms of rotors are described by Henke et al. (2018), and the potential directions of propagation of high-energy debris can be inferred from the behavior of failing blades and disks in turbo machinery as elaborated by Rossmann (2020). To mitigate this safety item (SI_05), an adequate physical containment and positioning of high-energy rotors is required. Therefore a failure and the subsequent spreading of debris will not pose a hazard to the occupants or prevent continued safe flight and landing. This proposal is in accordance with the requirements defined in CS 25.1461 by EASA (2023).

5. Conclusion

For this work, a coarse DEHPS design has been defined and the subsystems have been accordingly placed throughout the aircraft. Based on that design, lists of zonal safety items and according means of mitigation have been developed. All safety items emerge due to the interactions of novel DEHPS entities with each other or other entities in close proximity. The means of mitigation for the safety items have been developed based on literature review and expert knowledge and are discussed in section 4. The findings show, that the novel energy storage solutions (hydrogen, batteries) and their physical properties pose the greatest challenge in terms of intra- and cross-zonal safety. Some of the identified hazards and subsequent safety items are known and have been assessed in previous work (e.g., rotor disintegration), while others are novel and have not been addressed in the aerospace sector until now. Many of the identified novel hazards emerge in very vulnerable zones in the fuselage of the legacy aircraft where power, data and signal transmission lines are located or that are close to zone 200 that contains the cabin and cockpit. These novel hazards pose significant challenges for the integration into the legacy aircraft, emphasizing the necessity for novel aircraft designs. The conventional *tube and wing* aircraft design may not be suitable for the integration of DEHPS with hydrogen and batteries as primary energy carriers. To address these challenges, installation- and design requirements can be derived from the developed means of mitigation. These requirements can inform the design of novel aircraft concepts that employ DEHPS concepts, preventing the identified hazards from emerging and ensuring a continued safe flight and landing.

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