Toward Certification of Wing-Structure-Integrated Hydrogen Tanks: A Cross-Industry Review of Relevant Standards

Keywords: Structure-integrated hydrogen tanks; High-pressure composite hydrogen tanks; Hydrogen standards in aviation; SWITH (Wing-Structure-Integrated Hydrogen Tanks);

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1 Abstract

Standards are not only crucial for obtaining certification for practical use but also provide essential guidance on what to simulate and how to conduct experimental tests. This study examines the potential applicability of existing standards from various domains, including aerospace and automotive, to **W**ing-**S**tructure-**I**ntegrated high-pressure **H**ydrogen **T**anks (SWITHs). It highlights the associated challenges and uncertainties, acknowledging the absence of a single, all-encompassing standard for SWITHs. We conduct a thorough investigation to identify the most suitable existing standards that could serve as viable alternatives to a dedicated SWITH standard. Our analysis scrutinizes existing standards that could facilitate SWITH certification, with particular emphasis on accommodating externally loaded hydrogen tanks. Assessment criteria are established to determine the standards that best meet the needs of SWITHs, through which we pinpoint four key standards as the most promising alternatives. Moreover, we delineate the technical constraints involved in selecting the maximum nominal working pressure for high-pressure tanks intended for burst tests. Our findings reveal a current upper limit of 525, bar, imposed by the limitations of existing test facilities. The study underscores that these standards should serve as flexible guiding frameworks rather than rigid protocols, thereby encouraging progressive development in the field of SWITHs.

2 Introduction

The aerospace industry continually seeks innovations to improve fuel efficiency [142, 112, 15], reduce aircraft weight [26, 4, 143, 123, 68], and enhance overall performance [138, 61, 110]. One such development is the concept of **W**ing- **S**tructure-**I**ntegrated high-pressure **H**ydrogen **T**anks (SWITH), pronounced *sweets*, which are embedded within an aircraft's wing structure. An illustrative depiction of a SWITH is provided in Figure 1. The main difference between integrated and externally stored fuel tanks is that integrated tanks are designed to carry external loads and support the aircraft's load-bearing components. In contrast, external tanks are employed solely for fuel storage and supply. They are not an integral part of the structure, thus they are not designed to support the load carrying structure by absorbing the loads. In addition to wing-integrated hydrogen tanks, hydrogen storage can also be incorporated into the fuselage [34, 127, 62, 28, 5, 63, 125, 18, 151, 126, 152]. Both wing-integrated and fuselage-integrated hydrogen tanks can utilize either liquid or gaseous hydrogen; however, this contribution focuses on gaseous SWITHs.

The primary advantage of integral tanks is that the substantial space, which would have otherwise been reserved for fuel, becomes available for other purposes. For example, the same configuration can now be equipped with additional seating to transport more passengers. Alternatively, it could carry more cargo or large, cumbersome items that do not exceed the size of the original tanks. The concept of SWITHs has progressed beyond a mere scientific idea; for instance, APUS [13], an aircraft manufacturing company, is actively developing its i-2 model in an effort to introduce the first commercially available SWITH [14]. Nonetheless, despite these promising advancements, the relatively new SWITH concept still faces challenges related to manufacturing, safety, uncertain regulatory frameworks, and a scarcity of literature.

Given the complexity and innovation of SWITHs, it is essential to initiate a collaborative effort across researchers to address each individual hurdle. Each of the mentioned points can be expected to require many scientific groups to explore and find possible solutions. At the time of writing this paper, there are no known standards or regulations that could be applied to obtain certification. Without a certification that is recognized by local and global authorities, industrial and scientific employment of SWITHs is severely limited. Thus, there is an obvious demand for proper standards upon which industry and scientific institutions can rely. The latter not only serves to obtain certification but can also assist designers in their development processes. Aircraft design and production represent a highly complex and multidisciplinary endeavor [160, 113, 54, 159, 161]. As a consequence, the associated certification guidelines are intricate and encompassing. Moreover, due to the exacting quality standards in aviation, even minor modifications can necessitate exhaustive investigations before an approval for certification is granted [133, 114]. While the latter is insightful for enabling secure personal air transportation, the consequences for SWITHs are significant. Firstly, it is important to note that hydrogen, due to its highly reactive nature, possesses a combustibility range that extends to explosiveness [106, 25, 30, 145, 158, 17, 32]. Secondly, the typically sparse structure of many systems is supplanted by a cylindrical configuration [131, 21, 139]. When these two aspects are combined, we see the implementation of tube spars filled with pressurized hydrogen. These serve as the primary load-bearing structure, signifying a novel approach in structural design.

This development constitutes a significant deviation from conventional airplane designs, thereby necessitating extensive work before certification can be granted. Thus, the objective of this paper is to pave the way for this novel design by reviewing the current state-of-

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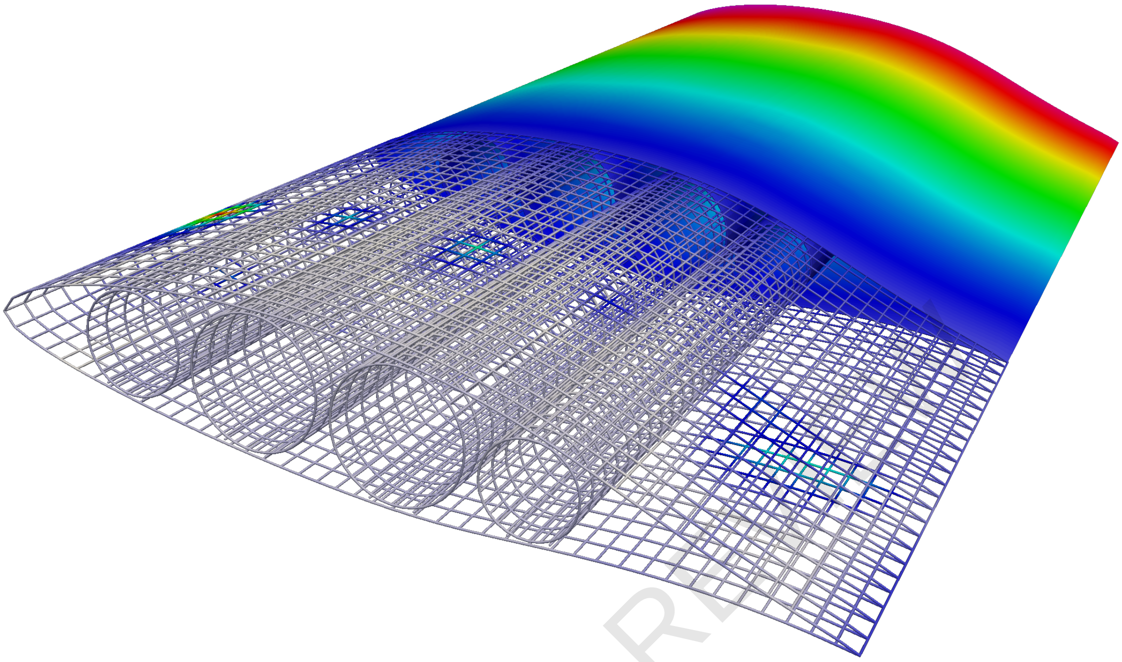

Figure 1: Illustrative example of a SWITH, similar to APUS i-2 [13]

the-art standards and regulations pertinent to the structural testing of SWITHs. In this context, we scrutinize applicable standards for various types of tanks, standards from diverse mobility sectors that employ pressurized cylinders, and hydrogen-specific regulations. Based on this comprehensive review, we first compile an extensive list of relevant standards and then formulate a set of evaluation criteria. Applying these criteria allows us to identify and present our top choices, which serve as the best available alternatives and a temporary baseline for the currently non-existent SWITH-specific certification standards. This baseline can provide the foundation upon which standardization and certification bodies can build, thereby contributing to the advancement of SWITH science and raising awareness of this transformative technology.

3 High-Level Aviation Standards and Their Relevance to SWITHs

Standards for **W**ing- **S**tructure-**I**ntegrated high-pressure **H**ydrogen **T**anks (SWITH) play a vital role in establishing a foundation for both design and experimental structural investigation, particularly when dealing with innovative concepts fraught with potential risks and uncertainties. Recognizing standards as guidelines allows engineers and specialists to follow a safe, clear, and systematic process [133, 114, 120, 162, 102, 118]. The contributions of experts to the development and revision of these standards ensure that considerations which an individual might overlook, are addressed, thereby enhancing the safety and reliability of products and systems. However, the absence of a comprehensive standard that addresses the design and physical structural testing of SWITHs indicates the necessity of choosing a differ-

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ent approach. This entails subdividing SWITHs into two significant sub-categories: aviation and pressure tank standards.

Aviation standards revolve around three main elements: certification space, maximum take-off mass (MTOW), and the general type of flying object. Certification space encompasses the designated region for the aircraft's certification and operation, regulated by specific authorities. MTOW refers to the maximum weight an aircraft can safely carry for take-off and flight, with distinct MTOW classes defined within the standards based on the aircraft's size and performance. The general type of flying object classifies the aircraft [107, 146, 109], including commercial large aircraft [103], helicopters, small aircraft [156], and military aircraft [128, 124]. General aviation standards in the EU are denoted as **C**ertification **S**pecification (CS). The CS standards that might be relevant to SWITHs are CS-23, CS-25, CS-27, and CS-29. For instance, CS-23 can be applied for the certification of a small aircraft that falls within specific criteria regarding its category, maximum take-off mass, and passenger capacity.

However, exceeding these criteria may require the application of CS-25, which necessitates a more detailed examination of various aircraft systems due to increased performance demands and complexities. The intent of this paper is not to delve into a comprehensive explanation of the CS standards, as such an exhaustive discussion would exceed the scope of this document. Instead, Table 1, which enumerates SWITH-relevant and several additional CS standards alongside their respective application fields, should suffice as a suitable reference. The counterparts on the US side are not mentioned because they are very similar in scope. This similarity even extends to the numbering of the documents and their respective paragraphs [115].

CS	**Field of application**
CS-22 [51]	Sailplanes and Powered Sailplanes
CS-23 [49]	Normal, Utility, Aerobatic and Commuter Aeroplanes
CS-25 [43]	Large Aeroplanes
CS-26 [48]	Additional airworthiness specifications for operations
CS-27 [40]	Small Rotorcraft
CS-29 [39]	Large Rotorcraft
CS-31GB [41]	Gas Balloons
CS-31HB [42]	Hot Air Balloons
CS-31TGB [46]	Tethered Gas Balloons
CS-LSA [44]	Light Sport Aeroplanes
CS-P [45]	Propellers
CS-VLA [50]	Very Light Aeroplanes, see also CS-23 [49]
CS-VLR [47]	Very Light Rotorcraft

Table 1: Selected EU civil aviation **C**ertification **S**pecification (CS) standards and their primary application fields.

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Starting with small aircraft, no applicable requirements or guidelines for high-pressure hydrogen containers could be identified within CS-23. In contrast, CS-25 Amendment 27 (CS 25.1453) contains guidelines for protecting oxygen equipment from rupture. Here, it is stipulated that the cylinder must be designed to sustain the working pressure of the oxygen cylinders, accounting for the maximum working pressure, transient pressures, pressure surges, pressure relief device tolerances, and possible pressure fluctuations during normal operating conditions. CS 25.1453 provides additional details. Among these details is a list of proof and burst factors for pressurized vessels intended for structural testing. These appear in Table 13, where the safety factors are shown in the denominators of the fractions. For the complete description of CS 25.1453, the reader is referred to the original source [43].

Systems element	**Proof factor**	**Burst factor**
Cylinders (i.e. pressure vessels)	1.5	2.0
Flexible hoses	2.0	4.0
Pipes and couplings	1.5	3.0
Other components	1.5	2.0

Table 2: Proof and burst factors for pressurized components. Table copied from CS 25.1453 [43] - Protection of oxygen equipment from rupture

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Notably, the category *other components* in Table 2 may offer requirements for strength verification, which could be adapted for SWITHs. One might evaluate the possibility of convincing approval authorities to accept a test factor of 1.5 and a burst factor of 2.0 for SWITHs through persuasive argumentation. EASA might potentially classify voluminous high-pressure tanks as *other components* (see Table 2). In contrast, two key counterarguments exist. First, the hydrogen tank is a pressure vessel with an internal pressure significantly higher than that of oxygen bottles. Second, the tank's dimensions are notably larger than those of an oxygen bottle. This straightforward reasoning could be employed by approval authorities to reject the proposed factors of 1.5 and 2.0. Consequently, it is prudent to examine aerospace-related areas more closely.

Another standard that might be considered to offer some guidance for SWITHs is the ANSI/AIAA S-081B-2018 Space Systems-Composite Overwrapped Pressure Vessels standard [11]. It is primarily applicable in the United States. Other regions have been known to reference established standards to develop their own [115], although there is no assurance of universal acceptance. The applicability of foreign standards typically depends on the adopting location, with international standards gaining global recognition, followed by continental and national standards. It is noteworthy that individual countries may impose additional requirements, significantly impacting novel projects. Two other prominent examples for SWITHs are provided by SAE International and are listed in Table 3. They announced preliminary drafts of standards related to liquid [136] and gaseous [135] hydrogen-powered aircraft in November 2019 and June 2021, respectively.

It should be explicitly noted that these standards have solely been announced and are not yet available for purchase as of the writing of this article. Assuming that an institution such as SAE International is aware that the ANSI/AIAA S-081B-2018 standard was published in 2018, the following issue deserves attention. SAE had approximately five years to draft the general-aviation standard for liquid hydrogen. If we consider that these five years were not sufficient, it suggests that the ANSI/AIAA S-081B-2018 Space Systems standard cannot be directly applied to general aviation without significant modifications. Furthermore, even if SAE AS 7373 [135] were available, it would not necessarily account for external loads on high-pressure hydrogen tanks. Hence, it remains unclear whether these standards, once completed,

Hydrogen physical state	**Standard**	**Announced since**
Liquid	SAE, AS 6679 Liquid Hydrogen Storage for Aviation [136]	20.11.2019
Gaseous	SAE, AS 7373 Gaseous Hydrogen Storage for General Aviation [135]	06.07.2021

Table 3: Overview of SAE standards for hydrogen storage in general aviation that have been announced but are yet to be published.

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will be applicable to structurally integrated high-pressure hydrogen tanks.

The other sub-category of SWITHs revolves around pressure tank standards, applicable to tanks holding high-pressure compressed gas [105, 27, 16]. The selection of an appropriate standard depends on various factors, including the pressure range [108, 157], the type of gas, the storage method [27, 104, 119, 153], the tank material [139, 140, 117, 19], and its intended application [130, 58, 137, 19, 111]. Given the numerous variables involved, combined with the innovative nature of SWITHs, which introduces additional uncertainties—and the absence of a dedicated certification standard—relying on a single standard would not be a viable approach. Consequently, a list of potential standards is provided in Section 4, while an evaluation of the most suitable ones is presented in Section 5.

In summary, while certain aerospace standards could provide useful insights for SWITHs, their applicability remains uncertain due to geographic and technical constraints. Current standards may not be entirely suitable for SWITHs, necessitating the development of a unique standard that encompasses the specific requirements of this niche area. Announced standards could partially support the certification of SWITHs. However, it remains unclear whether these standards incorporate the concept of externally loaded hydrogen tanks.

4 Cross-Industry Review of High-Pressure Hydrogen Standards

Given the automotive industry's advanced experience with high-pressure propulsion systems, a comprehensive review of relevant standards across various sectors has been conducted. This survey extends beyond aviation to sectors utilizing high-pressure tanks for propulsion and independent mobile applications. Particular attention is given to ISO standards relating to hydrogen applications, owing to their broad acceptance and relevance.

Key sectors under consideration range from automobiles [67, 66, 147, 60, 116], buses [129], and heavy-duty trucks [52] to industries where hydrogen-powered propulsion is either a concept or already a reality. It is critical to note that these sectors share common environmental motivations, aiming to reduce emissions attributed to transportation and mobility applications that contribute substantially to environmental degradation [132, 6, 10, 3, 53]. However, each industry presents unique challenges and design requirements, influencing the applicability of available standards.

Aerospace, automotive, and motorcycle industries [52, 129, 154, 65, 64, 155, 31] for example, differ significantly in pressure vessel positioning and operating conditions. Ground-level vehicles experience minimal pressure variation compared to aircraft designed for variable flight altitudes and the associated pressure differences [55]. This discrepancy results in elevated structural design stresses in aviation. Temperature variations with altitude [1, 121, 23] are another factor that warrants consideration. In aviation, optimizing weight and space is crucial for maximizing passenger and cargo capacity, thereby enhancing economic efficiency. This emphasis on efficiency also highlights the importance of distinguishing between light and heavy mobility solutions in hydrogen-powered transportation.

Various standards and projects have been identified that address compressed hydrogen as a fuel for light mobility, as enumerated in Table 4. Comparable standards for heavy-duty mobility, general pressurized cylinders without a clearly defined mobile application case, and ground-level static pressurized storage standards are outlined in Tables 5 to 7, respectively. For easier access a comprehensive overview of the previously mentioned aerospace standards are consolidated in Table 8. This arrangement allows all relevant information to be conveniently accessed in one location.

Light-Duty Vehicles		
	• EC 79/2009 [37] • EC 406/2010 [36] • UNECE R134 [38] • GTR No. 13 [56] • CSA/ANSI HGV 2-2014 (R2019) [9] • SAE J2579 [134] • KHK S0128 [69] • JARI S001 [99, 150]	• JARI S002 [98, 150] • JARI S003 [100, 150] • EIHP [35] • ISO 15869:2009, status: withdrawn [95] • ISO 19881:2018, announced to be updated [75] • ISO/DIS 19881, under development [91]

Table 4: Selection of standards for light-duty vehicles, image [59]

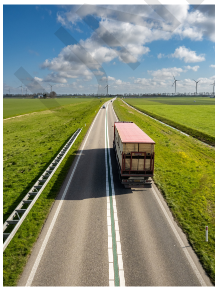
Heavy-Duty Vehicles	
	• EC 79/2009 [37] • EC 406/2010 [36] • CSA/ANSI HGV 2-2014 (R2019) [9]

Table 5: Selection of standards for heavy-duty vehicles, image [22]

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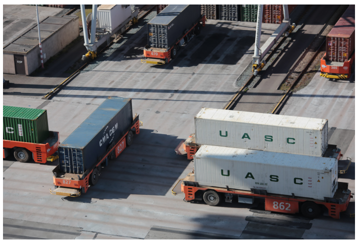
Transportable Tubes		
	• Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) [148]	• EN 12245, status: withdrawn [57] • U.S. DOT [141] • Apragaz TPED [12] • ISO 11119-3:2020 [2] • ISO 17519:2019 [96]

Table 6: Selection of standards for transportable tubes, image [33]

Ground and Stationary Storage	
	• Pressure Equipment Directive (PED) [149] • American Society of Mechanical Engineers (ASME) [122] • EN 12245 [57] • ISO 19884 [79]

Table 7: Selection of standards for ground and stationary storage, image [29]

General Aviation and Space	
	• **Aviation** – SAE AS 6679 [136] Liquid Hydrogen Storage for Aviation - Work in progress, started on 20.11.2019 – SAE AS 7373 Gaseous Hydrogen Storage for General Aviation [135] - Work in progress, started on 06.07.2021 – CS 25 - Large Aeroplanes • **Space:** ANSI/AIAA S-081B-2018 Space Systems—Composite Overwrapped Pressure Vessels [11]

Table 8: Selection of standards for general aviation and space, image [20]

ISO boasts a sterling reputation globally, significantly enhancing its prospects for partial or potentially complete international recognition. ISO standards pertaining to compressed hydrogen are numerous and comprehensive. The ISO standards dealing exclusively with hydrogen have been compiled in Table 9. While each ISO standard provides valuable insights for its respective hydrogen application domain, not every standard will be explored in detail

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here. An exhaustive review of all standards would be inefficient, requiring disproportionate time for only minimal additional value. Instead, Section 5 proposes a more focused approach. The suggested strategy consists of distilling the multitude of existing standards down to a select few that are most critical and relevant to the SWITH context.

ISO/TC 197 Hydrogen technologies	**Description**
ISO/AWI 14687	Hydrogen fuel quality — Product specification [70], status: available and new version under development [86]
ISO/AWI TR 15916	Basic considerations for the safety of hydrogen systems [94], status: available and new version under development [84]
ISO/AWI 17268	Gaseous hydrogen land vehicle refueling connection devices [71], status: available and new version under development [87]
ISO/AWI 19880-5	Gaseous hydrogen — Fuelling stations — Part 5: Dispenser hoses and hose assemblies [72], status: available and new version under development [88]
ISO/CD 19880-6	Gaseous hydrogen — Fueling stations — Part 6: Fittings [85], status: under development
ISO/WD 19880-7	Gaseous hydrogen — Fuelling stations — Part 7: O-rings [89], status: under development
ISO/AWI 19880-8	Gaseous hydrogen — Fuelling stations — Part 8: Fuel quality control [73], status: available and new version under development [90]
ISO/AWI 19880-9	Gaseous hydrogen — Fuelling stations — Part 9: Sampling for fuel quality analysis [74]
ISO/AWI 19881	Gaseous hydrogen — Land vehicle fuel containers [75], status: available and new version under development [91]
ISO/AWI 19882	Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers [76], status: available and new version under development [92]
ISO/AWI 19884-1	Gaseous Hydrogen - Pressure vessels for stationary storage Part 1: Part 1: general requirements [79], status: under development
ISO/AWI TR 19884-2	Gaseous Hydrogen - Pressure vessels for stationary storage Part 2: Material test data of class A materials (steels and aluminum alloys) compatible to hydrogen service [82], status: under development
ISO/AWI TR 19884-3	Gaseous Hydrogen - Pressure vessels for stationary storage Part 3: Pressure cycle test data to demonstrate shallow pressure cycle estimation methods [83], status: under development
ISO/CD 19885-1	Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 1: Design and development process for fuelling protocols [77], status: under development

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ISO/AWI 19885-2	Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 2: Definition of communications between the vehicle and dispenser control systems [80], status: under development
ISO/AWI 19885-3	Gaseous hydrogen — Fuelling protocols for hydrogen-fuelled vehicles — Part 3: High flow hydrogen fuelling protocols for heavy duty road vehicles [81], status: under development
ISO/AWI 19887	Gaseous Hydrogen — Fuel system components for hydrogen fuelled vehicles [78], status: under development
ISO/AWI 22734-1	Hydrogen generators using water electrolysis — Industrial, commercial, and residential applications — Part 1: General requirements, test protocols and safety requirements [93], status: under development
ISO/AWI TR 22734-2	Hydrogen generators using water electrolysis — Part 2: Testing guidance for performing electricity grid service [97], status: under development

Table 9: Standards following the *ISO/TC 197 - Hydrogen technologies*

In summary, the landscape of hydrogen utilization spans a broad range of sectors, from conceptual stages to established, commercially available technologies. While some sectors have made significant advances, unique industry requirements often limit the direct transferability of their existing concepts and standards to other areas, such as aviation.

5 Key Standards Identified: Main Results

After an extensive survey of standards for compressed hydrogen applications across multiple sectors, this section evaluates their applicability to SWITHs. To achieve this goal, criteria are developed to isolate pertinent standards from the vast pool available. The insights derived from this process form the bedrock of this work. In light of structural tests, this section also highlights the safety factors for burst tests and the maximal feasible nominal pressures. Because experimental tests are both costly and time-consuming, they are often preceded by simulations. As a result, simulation data can be extremely valuable for guiding experimental studies.

Table 10 presents three primary categories that should enable proficient standard users to promptly assess their applicability. These categories can be combined in various ways. For example, one possible combination is mobile, Type IV, and ground; another is static, Type IV, and ground. Both combinations are conceivable in practice. Considering the variety of potential combinations, standard selection must be carried out scrupulously to best meet the requirement profile. In the current framework, the selection is mobile, Type IV, and air, a choice expected to be suitable for both small and larger aircraft.

The three overarching categories that facilitate a rapid initial assessment of standards' applicability by experienced personnel are listed in Table 10. These categories - Storage, Tank Type, and Locality - can be combined in various ways to create specific requirement profiles. For instance, a profile might include *mobile* (Storage), *Type I* (Tank Type), and either *air* or *ground* (Locality). The multitude of possible combinations necessitates careful standard selection to ensure precise alignment with the specific requirement profile. This

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approach allows for tailored standard application, which is crucial for addressing the unique demands of different hydrogen storage systems, including SWITHs.

Storage	**Tank Type**	**Locality**
stationary	I	under water
mobile	II	under ground
-	III	ground
-	IV	air
-	V	-

Table 10: Overarching categories for hydrogen tank applications to guide standard selection.

In accordance with the categories outlined in Table 10, a SWITH falls under the classification of mobile, Type IV, and air. The term *air* in this context is self-evident, referring to the operational environment of aircraft. However, the distinction between *mobile* and *static* pressure vessels requires further elucidation. Mobile pressure vessels are characterized by their exposure to forces resulting from acceleration, encompassing both linear and angular components. These vessels experience dynamic loading conditions due to the motion of their host vehicle, whether that vehicle is an aircraft in flight or an automobile on the road. Conversely, static pressure vessels are subject solely to the force exerted by their own mass under the influence of gravity. In static applications, the pressure vessel does not undergo any additional accelerations beyond those imposed by Earth's gravitational field. The rationale for selecting tank Type IV lies in its technological maturity [139] and its significant weight advantage over Types I, II, and III [153, 101, 27, 130]. However, the reservation against Type V pertains to its prohibitive cost and limited availability [8, 7, 144, 27].

Table 11 presents the criteria for determining essential standards, with no specific weighting implied by their order. The first two criteria are obvious prerequisites for passing the initial stage of filtering. Yet, of particular importance for pioneering projects like SWITHs are these first two criteria: *Timeliness* and *Active development*. These interlinked criteria are crucial in ensuring that standards remain relevant and effective. Timeliness ensures that standards incorporate the most recent knowledge from expert teams. Active development, on the other hand, serves as a mechanism to adapt standards within a reasonable time frame after new information becomes available. Together, these criteria reflect the iterative process of standard creation and revision, whereby new insights are integrated to address challenges and refine existing guidelines.

1) Timeliness
2) Active development
3) Accessibility and availability
4) Adoption in research and industry
5) International recognition
6) Europe-wide recognition
7) Costs for acquisition
8) Coverage of SWITH requirements
9) Clearly understandable and detailed specifications,

Table 11: Criteria for evaluating and selecting the most relevant alternative standards for SWITHs in the absence of a dedicated standard

In innovative projects such as SWITHs, learning often occurs through trial and error. Standards play a crucial role in this process by capturing accumulated knowledge and pre-

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venting the recurrence of past mistakes, both major and minor. As these projects evolve, standard-issuing bodies must adapt their guidelines by refining or even removing requirements to reflect best practices identified through practical implementation. These adaptations, which aim to ensure safety and functionality for both people and the environment, facilitate the transition from manufacturing to certification and ultimately enable commercial adoption. By codifying insights gained through iterative development, standards serve as a repository of collective expertise, guiding researchers and industry professionals. Prioritizing standards that are both current and actively maintained ensures alignment with the latest advancements. This approach enhances safety, efficiency, and regulatory compliance while fostering continuous innovation on a solid foundation of established knowledge.

The *accessibility and availability* criterion, as outlined in Table 11, is of paramount importance. Even the most comprehensive standards hold little value for research and industry if they are not readily obtainable. Criteria 4-6 in Table 11 (*Adoption in research and industry, International recognition, and Europe-wide recognition*) act as indicators of a standard's experience and successful implementation. The trustworthiness of a standard correlates with the frequency of its adoption and the number of functional vehicles successfully constructed and approved based on its guidelines. A standard's international recognition often follows from its established trustworthiness. Nevertheless, in the absence of internationally recognized standards, the focus shifts to regional standards. The *cost of acquisition* plays a decisive role, particularly for start-ups and small to medium-sized research and industrial institutions. These entities often operate under constrained budgets, making affordability a key factor in standard selection. The *coverage of SWITHs* requirements is a critical criterion. It is generally understood that any standard failing to account for this aspect would be automatically disqualified from assessment. This criterion acts as a fundamental filter, ensuring that only relevant standards are included in the selection process.

The final criterion, *clearly understandable and detailed specifications*, is essential for effective implementation. Standards should provide precise and comprehensive guidelines to ensure consistent application across different projects and organizations. This clarity facilitates accurate interpretation and implementation, reducing the risk of errors or misunderstandings that could compromise safety or performance in SWITH applications. For SWITHs, four standards meeting all criteria and complementing each other have been identified in Table 12.

1) EC 406/2010 [36]	2) ISO 11119-3:2020 [2]
3) CS-23 [49]	4) CS-25 [43]

Table 12: Selection of four essential standards that, while not fully covering all aspects of SWITHs, collectively represent the current state of the art.

The selected standard EC 406/2010 [36] is an established regulation for the automotive industry. However, direct application to aviation brings forth some reservations. First, the English title for EC 406/2010 seemingly allows for its application to aircraft, while its German translation restricts it to motor vehicles. The ISO 19881:2018, which has similar purposes as EC 406/2010 , explicitly limits its scope to land vehicles and permanently attached tanks through its document's title. The words *Land vehicles* make it clear that an application for aircraft is not permitted. Besides the language aspect, a review of EC 406/2010 reveals that it makes no direct reference to aircraft use. Another potential limitation of EC 406/2010 is its stringent testing requirements, which may exceed available economic resources. For example, multiple SWITH specimens are required for a single test, a demand that is also present in ISO 11119-3:2020 [2]. The requirement for multiple SWITH samples is particularly problematic due to the cost- and time-intensive nature of their manufacturing. For SWITH applications, composite tubes can range from 7–15 meters in small aircraft and up to about 80 meters in larger aircraft. Furthermore, based on technological advancements demonstrated by APUS [14], the current state of the art favors multiple cylindrical tubes rather than a single airfoil-shaped, high-pressure hydrogen tank. The combination of large component dimensions, composite materials, and the innovative nature of the design significantly increases manufacturing costs. As a result, requiring multiple SWITH specimens for experimental testing can be regarded as prohibitively expensive.

Another obstacle to applying EC 406/2010 directly to SWITHs arises from certain prescribed requirements, which may be deemed overly stringent. These demands are found identically in EC 406/2010 and ISO 19881:2018, pertain to the gaseous hydrogen burst ratio criteria. These requirements are specified in Section 3.6 of EC 406/2010 and Section 7.3.2 of ISO 19881:2018. They mandate that Equation (1) to be fulfilled. The variables p_{brust}, $factor$ and p_{wnp} are denoted as the minimal burst pressure, a factor depending on over-wrap material and the nominal working pressure, respectively.

$$p_{brust} \geq factor \cdot p_{wnp} \tag{1}$$

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For glass, aramid, and carbon fibers, the factors are 3.5, 3.0, and 2.25, respectively. Putting these in words, if aramid is deployed as the wrap material, the hydrogen tank must be able to withstand three times of its nominal pressure. Consequently, if the nominal pressure for a tank were set at 300 bar, the tank must be able to cope with at least 900 bar, without showing any sign of bursting. Thus, the high safety factors defined in EC 406/2010 and ISO 19881:2018 can be regarded as severe limiters. The higher the safety factors are, the more material will be required to meet these demands. More material results in increased weight, which is undesirable in modern weight-focused aviation. Moreover, the high-pressure gas tank testing facility of the European Commission (GasTeF) states in [24] that it is capable of testing at a maximum internal pressure of 1050, bar. Taking this as a reference, and considering the influence of wrapping material, the maximum working nominal pressures (p_{mwnp}) range from 300 bar to 465 bar. However, if the safety factors specified in ISO 11119-3:2020 are applied, the maximum working nominal pressures (p_{mwnp}) increase to a range of 437.5 bar to 525 bar. The summary of this passage is consolidated in Table 13, where the safety factors can be found in the denominators of the fractions.

Wraping material	**EC 406/2010 & ISO 19881:2018** p_{mwnp}	**ISO 11119-3:2020** p_{mwnp}
glass	$\frac{1050}{3.5} = 300$ [bar]	$\frac{1050}{2.4} = 437.5$ [bar]
aramid	$\frac{1050}{3.0} = 350$ [bar]	$\frac{1050}{2.1} = 500$ [bar]
carbon	$\frac{1050}{2.25} \approx 465$ [bar]	$\frac{1050}{2.0} = 525$ [bar]

Table 13: Maximal allowable working nominal pressure p_{mwnp} for different wrapping materials, if maximal allowed pressure equals 1050 bar [24] and safety factors for the burst test from three different standards

Nevertheless, despite its limitations, EC 406/2010 remains a viable candidate for inclusion among the selected standards. The observations that lead to disqualify the mentioned ISO

19881:2018 are some difficulties in proper understanding the instructions. Due to copyright restrictions, the original document will not be reproduced here. Instead, a description of the problem shall be provided. The issue centers on *Table 1 - Material tests.* This table comprises headers for material test, clause, material type, and four fields corresponding to the four possible tank or container types. For the category material type, multiple metal materials are listed, with each associated field for Type IV tanks marked as applicable. This layout suggests that these tests are mandatory not only for metal tanks but also for composite tanks. Given the significant differences between metal and plastic liners, some variations in the testing protocols should be expected. If no distinction is to be made, there should be an explicit statement to that effect. Thus, the question arises: Should composite tanks be tested in the same manner as metallic tanks, or are these tests exclusive to metallic tanks? Since these questions could not be resolved within a reasonable effort, ISO 19881:2018 was excluded from the selected standards.

Essential aspects of the selected standards include mandatory and optional tests from ISO 11119-3:2020, illustrated in tables 14 and 15, respectively. These tables are presented in this manner without copyright concerns, as they primarily list the names of the tests. A comparison of different standards revealed that similar test names would sometimes have very different test descriptions. Thus, the test names alone do not provide sufficient insight into the actual testing process. Nevertheless, the tables offer a general overview of the tests that may be required. It is important to note that some optional tests may become mandatory, depending on the specific circumstances of the project at hand.

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Mandatory: Name of test & (ISO 11119-3:2020 reference)

- hydraulic proof pressure test (8.5.1), or hydraulic elastic expansion test (8.5.2)
- cylinder burst test (8.5.3)
- ambient temperature cycle test (8.5.4)
- environmental cycle test (8.5.6)
- flaw test (8.5.8)
- drop/impact test (8.5.9)
- high-velocity impact (gunfire) test (8.5.10)
- torque test on cylinder neck boss (8.5.13)
- leak test (8.5.15)
- pneumatic cycle test (8.5.16)
- resin shear strength (8.5.18)
- glass transition test (8.5.14)

Table 14: Mandatory tests required for a new gas cylinder, as specified in ISO 11119-3:2020 [2].

In conclusion, four key standards were identified as the most promising alternatives to the currently missing comprehensive SWITH standard. The aircraft certification specifications CS-23 and CS-25 were included among the best alternatives, as they provide critical information on aircraft testing requirements that other documents do not cover. Collectively, these four key standards offer significant insights, despite their indirect applicability to SWITHs. Furthermore, it was demonstrated that the nominal working pressure can reach up to 525, bar, depending on the applicable standard. This limitation arises from the fact that existing test facilities are unable to generate arbitrarily high pressures for experimental verification.

Optinal: Name of test & (ISO 11119-3:2020 reference)
vacuum test (8.5.5) (mandatory if a cylinder is to be exposed to a vacuum in service)
environmentally assisted stress rupture test (8.5.7) (mandatory for cylinders with load-sharing glass or aramid fibre)
permeability test (8.5.12) if cylinders are manufactured with non-metallic liners or without liners
fire resistance test (8.5.11)
salt water immersion test (8.5.14) (mandatory for cylinders used in underwater applications)

Table 15: Optional tests for a new gas cylinder, as specified in ISO 11119-3:2020 [2], which may become mandatory under certain conditions.

6 Discussion

In summary, while certain aerospace standards could provide useful insights for **W**ing-**S**tructure-**I**ntegrated high-pressure **H**ydrogen **T**anks (SWITH), their applicability remains uncertain due to geographic and technical constraints. Existing standards may not fully meet the specific requirements of SWITHs, highlighting the need for a dedicated standard tailored to this niche application. Some announced standards may partially support the certification of SWITHs. However, it remains unclear whether these standards account for externally loaded hydrogen tanks. The landscape of hydrogen utilization spans a broad range of sectors, from conceptual developments to established, commercially available technologies. Although certain sectors have made significant advances, their industry-specific requirements often limit the direct transferability of existing concepts and standards to other fields, such as aviation.

Four key standards were identified as the most promising alternatives to the currently missing comprehensive SWITH standard. Collectively, these standards provide significant insights despite their indirect applicability to SWITHs. Furthermore, it was demonstrated that the nominal working pressure can be selected up to a maximum of 525, bar, depending on the considered standard. This limitation arises from the fact that existing test facilities are unable to generate arbitrarily high pressures for experimental verification. Finally, it is important to reiterate that these standards are intended to serve as guidance, providing a framework or reference point rather than dictating exact protocols or offering a ready-to-use standard specific to SWITHs.

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