Approach for classification of requirements and test conditions for safety-compliant testing of hydrogen components

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Abstract

Hydrogen is widely seen as one of the potential key energy sources of the future. Despite the existence of numerous guidelines specifying the tests required for certification of components in various fields, the potential dangers of hydrogen as a medium in test environments are not yet sufficiently taken into account. This work presents a classification-based approach to structure the requirements for tests with hydrogen-carrying components and to systematically derive measures that allow for efficient and safe tests within the demanded specifications. Finally, this approach is applied exemplarily to a cyclic test of a CFRP hydrogen tank.

Keywords

Hydrogen, Testing, Requirements

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1. Introduction

Hydrogen in liquid or gaseous form has been regarded as a potential source of sustainable energy and fuel for several decades and is already in use as such in different industry branches [1]. The prospect of hydrogen fueled aircraft, while a known research field for many years [2, 3], has not seen broad practical application until now. With the introduction of the European Union roadmap towards the decarbonisation of the aviation sector and its revision in the current Strategic Research and Innovation Agenda (SRIA) [4] as well as national programs pushing for an energy transition [5], hydrogen technology has also become a focus of research into propulsion of next generation aircraft.

Whereas several guidelines exist dealing with safety and certification requirements of hydrogen carrying components along the entire hydrogen value chain, e.g., electrolysis hydrogen generators [6], tanks [7], fuel cells [8] and road vehicles [9], no such standards are currently in place covering the specific requirements for certification of hydrogen carrying aircraft components [10, 11]. However, the challenges arising from the clash of hydrogen technologies reaching higher technology readiness levels (TRL) and the gaps in certification guidelines have been repeatedly discussed [12–14]. In particular, these include the need for properly defined test conditions and specifications in the regulations for certification of aircraft components under consideration of the special properties of hydrogen as a medium in different conditions.

The definition of standards and tests for certification is – while a necessary step forward – not a solution in itself, as this opens up the question of implementation. Hydrogen is a strongly reactive medium with a very low ignition energy [15] and thus poses a potential danger not only to, e.g., passengers of hydrogen-fuelled aircraft or vehicles, but also to the personnel and facilities conducting tests during both product development and certification. Some guidelines on the safe storage, handling and use of hydrogen in liquid or gaseous form are provided, e.g., in the NASA Technical Standard NSS 1740.16 [16], however, those mostly cover general measures to create a safe work environment such as exclusion areas, general fire protection, transportation and setup of storage facilities.

In summary, the current push towards hydrogen-based technologies in different industry branches and particularly in the aircraft sector, while facing a number of different challenges regarding the eventual certification of newly developed components and products, is also confronted with the question of how tests during development and certification processes can be carried out in a safe and efficient manner. The infrastructure and equipment necessary to safely use hydrogen in a testing environment and comply with the specifications regarding potentially explosive atmospheres outlined in the ATEX 2014/34/EU guidelines [17] are not easy or cheap to obtain for research institutes and laboratories that specialise in certification tests for various applications. Hence, this contribution aims to provide a means to support researchers and test engineers in classifying and categorising the potential dangers of different test configurations and the resulting requirements for safely conducting said tests. The application of the developed approach is then demonstrated in a preliminary experimental study on hydrogen tanks made of Carbon Fibre Reinforced Plastic (CFRP) in cyclic loading.

2. State of the art

2.1. Hydrogen technology

Hydrogen based technologies, in particular hydrogen fuel cells, have been an established focus in different research areas for many years. Hydrogen gas is usually stored in high-pressure tanks at 200 to 700 bar, depending on application type and volume of the tank [18]. To circumvent the necessity of high-pressure vessels and the large volume required, hydrogen is also often stored at cryogenic temperatures below -253°C as Liquid Hydrogen (LH2), which possesses a much higher energy density [1, 3]. One of the biggest known risks in the use of hydrogen is its very low ignition energy when diffused in air, at 0.02 mJ, as well as the broad range of flammability in air of 4% up to 75% in volume combined with the speed and heat of a potential combustion, which is significantly greater than in most other fuels [19].

Concepts for hydrogen or its derivatives as fuel for vehicles and stationary applications in general – be it on land, at sea or in the air – in many cases utilize fuel cells, which generate electricity from the reaction of hydrogen and oxygen [20]. This technology allows for more freedom in the design of the considered system, as electric motors or actuators can then be placed to power the respective machinery. A different solution considered especially for high speed aircraft propulsion systems is hydrogen combustion, e.g., in turbofan, ramjet or scramjet engines [3, 11]. A basic, generalised schematic setup for hydrogen energy systems is visualised in Figure 1. Here, the heat exchanger is marked as an optional component as it is only required when LH2 is used, which is stored at cryogenic temperatures, whereas the different sensors for monitoring pressures, temperatures, flow rates and other relevant parameters have been left out for better clarity. Naturally, the configuration of this setup in placement and number of components may differ significantly, depending on the specific application and individual concepts, see e.g., [11, 13, 14, 21].

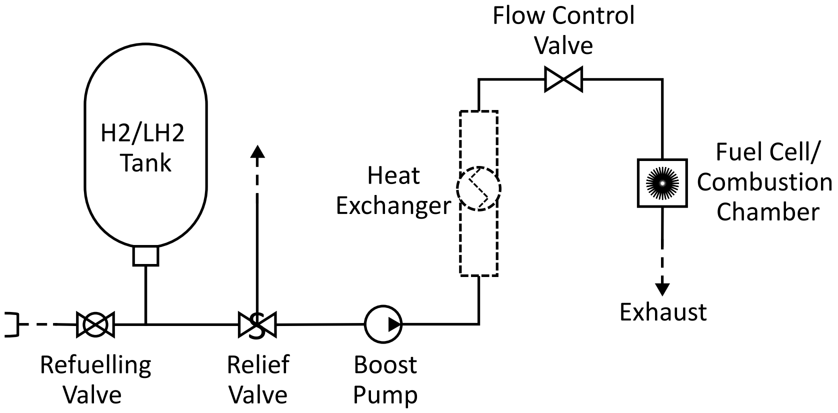


Figure 1: Simplified schematic setup of hydrogen fuelled systems

2.2. Certification and testing of hydrogen-carrying components

In most industrial applications, specific standards and guidelines exist which contain the required tests for certification of system-relevant components. For the automotive sector in particular, there are also guidelines regarding the certification of components for vehicles fuelled with gaseous hydrogen in the ISO 12619 series, e.g., [9, 22]. Here, it is specified that certification tests are to be carried out using helium, dry hydrogen or nitrogen blends with at least 5% hydrogen as test medium [22]. These standards however do not provide any guidelines or requirements on the test environment or equipment. Certification tests of aircraft components usually refer to the RTCA/DO-160 [23] for test conditions and procedures. With respect to the detection of potential ignition sources this guideline defines several approaches, one of which utilizes a combustible gas mixture containing 5% hydrogen, 12% oxygen and 83% argon. In addition, the RTCA/DO-160 also provides a framework of guidelines regarding both, test equipment and test environment [23]. However, this document currently does not consider hydrogen as a filling medium for components.

A framework applied to structure testing across different abstraction levels is the Product-Component-Test (PKT) Pyramid, as shown in Figure 2, which builds on the principles of the classical Building Block Approach originally developed in aeronautics [24]. The PKT Pyramid has been described and applied in various contexts, e.g. by Breuer [25] or Hartwich et al. [26], and was further extended to account for uncertainties [27] or the transferability of application-specific boundary conditions [28].

The pyramid distinguishes between tests on the material, component, and product level, providing a hierarchical scheme to increase structural complexity and reduce the number of required full-scale tests. At the material level, fundamental material properties and interactions with specific media, such as hydrogen, can be investigated under controlled laboratory conditions. The component level addresses sub-elements such as tanks, valves, or piping systems, where functional behaviour and damage tolerance under representative loads can be assessed. Finally, the product level focuses on the integrated system, ensuring overall safety and certification compliance under realistic operating conditions. Alongside the structural hierarchy, the PKT Pyramid is a three-sided model that includes the reality, physical test model, and virtual test model [28]. The reality side represents the operational environment and real system behaviour, while the physical test model provides experimentally accessible abstractions on different levels of complexity. Within the scope of safety-related requirements and experimental conditions in hydrogen testing, the virtual test model plays a subordinate role.

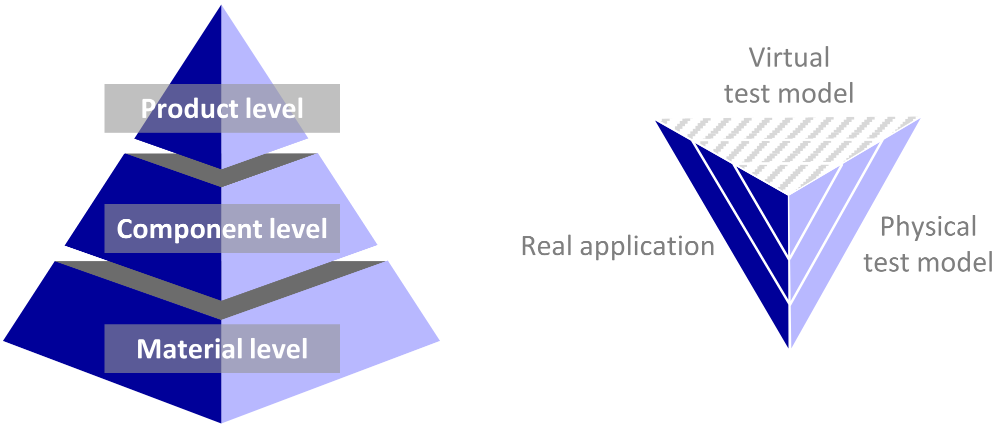


Figure 2: Product-component-test pyramid adapted from [28]

3. Research problem and objective

As outlined above, existing standards and guidelines dealing with test specifications for products and components in general, as well as those considering hydrogen-carrying components, usually focus on the certification process. However, numerous tests are also necessary during the different stages of the development of these products and components, for which the use of hydrogen or hydrogen-mixtures may pose disproportionate risks, cost and effort. Even though the danger of explosive atmospheres can be easily eliminated by using a non-flammable medium, utilizing any gas or gas blend for experiments or tests on pressure vessels or other pressurised components carries a significantly higher danger potential than the use of a non-compressible medium, e.g., in case of burst failure.

Thus, the goal of this work is the proposition of an approach that can serve as a framework in the decision process of selecting test conditions and test set-up for testing of hydrogen-carrying components. In order to ensure safety-compliance as well as efficiency, the different requirements of possible tests have to be considered. The variety of to be tested components and products, in conjunction with the number of different tests for each of those, opens up a wide spectrum of potential test conditions that is challenging to cover in detail by any one method or approach. Hence, the framework presented in this contribution is kept to a generalised level by relying on classification of test scenarios which can then be filled with specific details as necessary, as is shown in the exemplary application of this approach.

4. Approach for classification of test conditions in tests with hydrogen components

In order to methodically support the derivation and classification of the specific requirements for test conditions and environment based on the desired test scenario, the approach outlined in Figure 3 is proposed. As a first step, the complexity level of the considered test specimen should be clarified, in order to set a general frame for the specification of the necessary test environment, e.g., general requirements on the scale of physical dimensions or volume of test medium. Here, a categorisation according to the product-component-test pyramid is recommended, as in the generalised form it yields three distinct complexity levels that can be applied to any product. Some ambiguity is possible here for certain test specimens like tanks or valves as these can be viewed as either products of themselves or components in a larger system. This can be avoided by a clear definition of the system boundary and frame for the desired test.

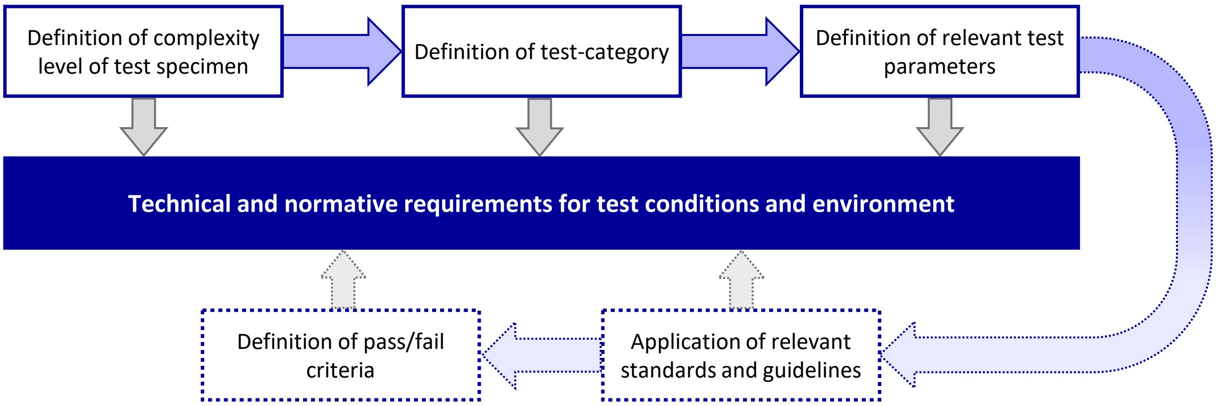
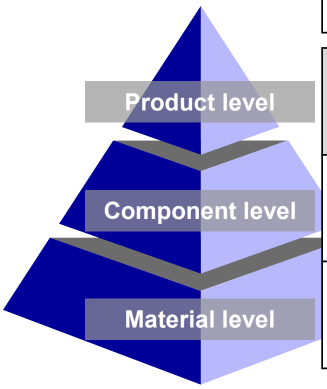


Figure 3: Schematic visualisation of the proposed approach

In the second step the desired test-category is defined, i.e. the type of behaviour that the test aims to investigate. This can be divided into three broad categories, material behaviour, structural behaviour and functionality. Tests focusing on material behaviour include, for example, the chemical interaction of the test specimen with hydrogen or the effects of cryogenic temperatures for LH2 applications on the microstructure. Among tests regarding the structural behaviour are often such that include potential destruction of the specimen, e.g., tests on mechanical failure strength, damage resistance and propagation, or crash and impact tests. Finally, tests that consider aspects such as general or lifetime performance, e.g., by way of operational safety or leakage in different conditions, can be categorised as functionality tests. From this classification, additional technical requirements are derived, further specifying the test conditions and refining the broad frame defined in the first step.

The definition of relevant test parameters is guided by combination of the defined complexity level and test-category in the third step. An exemplary overview over different possible constellations and the resulting potential test parameters of interest is given in Figure 4. The types of parameters and properties listed herein are purposefully kept mostly on a generalised level and are not exhaustive, as some structures, components or products may need to be tested for individual specific properties. At the same time, it is recommended in this step to precisely define relevant test parameters as well as all other values that should be recorded.



Material behaviour	Structural behaviour	Functionality
	▪ Structural durability ▪ Crashworthiness ▪ Vibration behaviour	▪ Functional durability ▪ System integration ▪ Operational safety
▪ Embrittlement ▪ Diffusion ▪ Material compatability	▪ Resonance frequencies ▪ Damage tolerance ▪ Mechanical failure modes	▪ Leakage ▪ Functional failure conditions ▪ Performance
▪ Chemical interaction ▪ Thermal properties ▪ Permeability	▪ Stiffness properties ▪ Strength properties ▪ Degradation behaviour	

Figure 4: Exemplary derivation of test parameters of interest based on complexity level and test category

The clarification and compilation of parameters of interest allows to systematically formulate further requirements, first on the technical aspects such as the types of measuring equipment and the capabilities of the test rig itself. Secondly, the combination of the categorisations from the previous steps and the specified goal of the test enable the derivation of requirements regarding the use of hydrogen in said test. If, for example, a test aims to investigate the embrittlement of a check valve mechanism exposed to LH2 over a service life, not only should hydrogen be used as a test medium but this medium also needs to be pressurised repeatedly. On the contrary, a test that pertains to the failure conditions of the connection between a high-pressure tank and a pipe under vibration and shocks is not reliant on the special properties of hydrogen and thus may be carried out more safely with a different filling medium. However, in this example the test medium still needs to be a gas of low density, such as helium, to avoid influencing the dynamic behaviour of the considered components as would be the case with a liquid. The choice of any test medium is also accompanied by normative requirements regarding safe handling of said medium and safety measures during tests.

At this point, all of the essential technical and normative requirements regarding the test conditions and test environment, as well as the test medium are sufficiently known. Depending on the test category and the general purpose of the test, these may be all necessary steps to achieve a comprehensive list of requirements, e.g., in case of a preliminary test of a structural component or prototype during the product development process. However, in any case it should be checked if the two further optional steps are applicable to the planned test. The first of these is the application of standards and guidelines of relevance to the test conditions, test procedures, measured data, or other technical or normative aspects. Following that, the last step is the precise definition of pass-fail criteria that specify the end of the test, e.g., a set number of loading cycles or failure of the test specimen in a burst test. Particularly when considering certification tests, these criteria are often also specified in the relevant standards.

5. Exemplary application of the developed approach

To demonstrate the applicability of the developed classification approach, a cyclic pressure test on a Carbon Fibre Reinforced Plastic (CFRP) tank was selected as an exemplary case study. The investigated test specimen is a Type III pressure vessel with a 0.3 L internal volume. It consists of an AL6061 aluminium alloy liner overwrapped with carbon fibre in the hoop and helical orientations and a glass fibre layer for enhanced impact tolerance. The tank is designed for a nominal working pressure of 30 MPa, a hydrostatic test pressure of 50 MPa, and a minimum burst pressure of 102 MPa.

Within the framework of the product-component-test pyramid, the present case is located on the component level, as the tank represents a distinct structural element within a larger system. The objective of the test is to evaluate the structural response of the composite overwrap and liner under cyclic pressurisation. Of primary interest are the strain evolution in the fibre-reinforced structure, the stability of the load response under repeated cycling, and the identification of potential damage initiation or degradation mechanisms. The pass/fail criteria are defined as (i) absence of leakage, (ii) absence of structural failure during the specified load cycles, and (iii) stable strain behaviour without progressive accumulation indicative of damage.

The following test conditions were derived based on these objectives. The tank is subjected to cyclic internal pressure loads between 5 MPa and 60 MPa, which corresponds to a stress ratio of R = 1/12. As the structural response to cyclic loading is the focus of this investigation, hydrogen as a test medium is not required. Instead, a nearly incompressible hydraulic fluid was selected to minimise the risk of catastrophic failure in case of tank rupture. As depicted in Figure 5, four strain gauges (SG) were mounted on the tank surface to record local strain behaviour, while a fifth gauge was employed for temperature compensation. In addition, a temperature sensor monitors the thermal behaviour during cyclic loading.

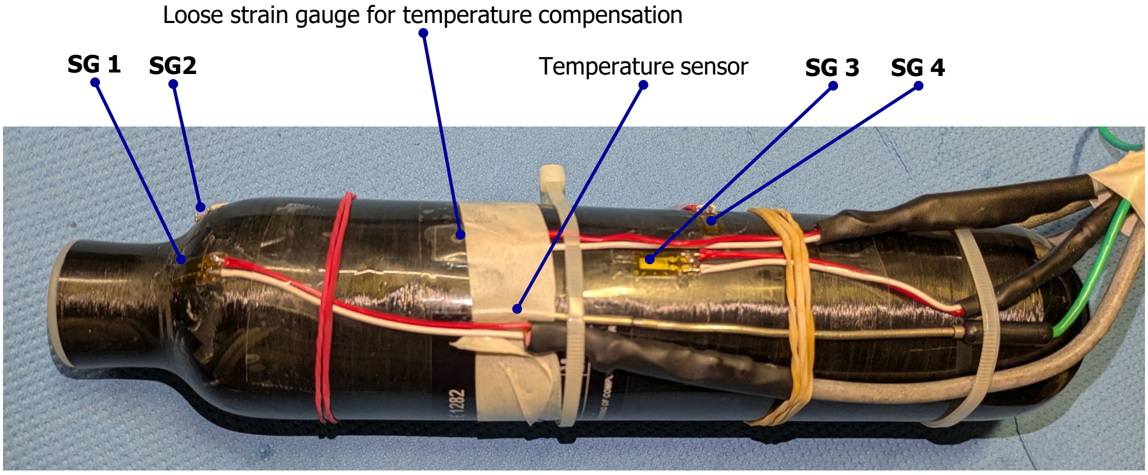


Figure 5: Tested CFRP tank with strain gauges and temperature sensor

The cyclic pressurisation of the CFRP tank led to different strain responses depending on sensor position and orientation. The most critical loading was observed in the hoop direction at the cylindrical midsection (SG 4), where maximum strain amplitudes reached approximately 3000 µm/m. In addition, the longitudinally oriented gauge at the vessel neck (SG 1) exhibited a negative R-value of -0.38, indicating alternating loading conditions. Such alternating stresses are of particular concern for fatigue, as they accelerate material degradation compared to pulsating loads. Table 1 summarises the measured maximum strain amplitudes and R-values for all gauges.

Table 1: Maximum strain amplitudes and corresponding R-values

Strain gauge	Position	Orientation	R-value	Max strain amplitude [µm/m]
1	Neck	0° (longitudinal)	-0.38	~400
2	Neck	90° (hoop)	0.27	~370
3	Midsection	0° (longitudinal)	0.20	~1660
4	Midsection	90° (hoop)	0.13	~3000

All strain gauges showed a run-in during the first loading cycles despite temperature compensation with SG 5. Furthermore, the signal recorded by SG 2 deviated from the expected sinusoidal behaviour of cyclic pressurisation (see Figure 3). Distortions were already visible at the beginning of the test. Possible explanations are local pressure surges due to valve dynamics, geometric effects in the neck region such as ovalisation or local buckling, fibre–

matrix inhomogeneities leading to non-linear stiffness responses, or complex stress states in the reinforcement transition zones. In summary, the results highlight two critical aspects for fatigue assessment: the high hoop strains in the cylindrical midsection and the alternating longitudinal loading at the neck. Both regions represent potential hotspots for fatigue-driven damage evolution.

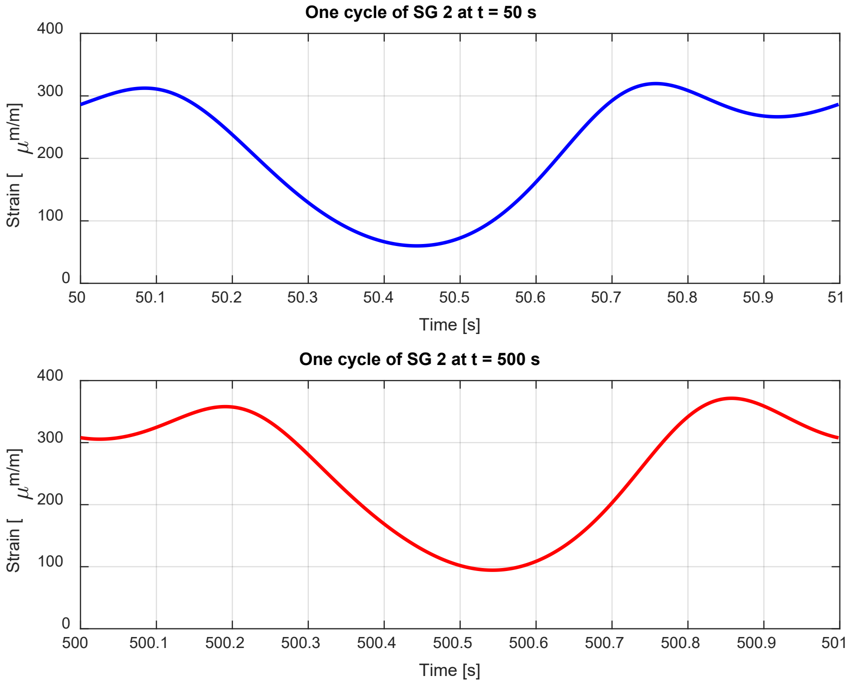


Figure 6: Strain signals of SG 2, showing deviations from ideal sinusoidal behaviour

6. Summary and outlook

Hydrogen technologies are a point of interest in several industry branches, however, standards for certification of hydrogen-carrying components are still lacking, particularly in the field of aviation. Whereas in some areas guidelines exist specifying the tests that need to be passed for certification, the realisation of these tests and the risks for personnel and equipment introduced by hydrogen as a test medium are usually not taken into account. Hence, a step-wise classification procedure for tests with hydrogen-carrying components is developed that allows for methodical compilation of requirements regarding test conditions and environment as well as the test medium, to enable test engineers to minimise potential dangers that can arise from the use of hydrogen.

The approach to safety-compliant tests with hydrogen carrying components outlined in this contribution represents a baseline framework whose applicability has been demonstrated in a preliminary experimental study on hydrogen storage tanks made of CFRP. Naturally, to validate the approach in full it is necessary to follow up with further test campaigns focusing on different levels and test objectives. In the future, this includes especially tests at higher complexity levels that do require the use of hydrogen as a test medium, in order to evaluate the width of application of this approach as well as possible edge cases and boundaries.

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