

Rationale for Performance-based Validation Testing of Compressed Hydrogen Storage

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ABSTRACT

This paper is a review of the technical rationale for performance tests to qualify new hydrogen storage systems to assure safety throughout service life. SAE J2579 is used as an example of performance-based requirements. This paper is intended to broaden understanding of requirements for testing compressed gas storage that are under development at SAE and ISO.

INTRODUCTION

The development of hydrogen-fueled fuelcell vehicles has been spurred by the combination of issues such as transportation's petroleum dependence, fuel costs, potential global warming and more traditional air quality. Standards enable commercialization by specifying interfaces and expectations for operation (so that components and systems made by diverse suppliers will work together) and by specifying requirements to ensure public safety. Requirements to qualify storage systems for onroad passenger vehicles have been under development primarily at the Society of Automotive Engineers International (SAE), and also at CSA-America and ISO.

The push to develop safety standards well before commercialization is driven by two factors. First, onroad safety is a high priority, so requirements must be developed preemptively, which means without waiting for the learning curve that can result from adverse onroad experiences. Second, the need for rapid insertion of new technologies into the marketplace is high – energy-saving products must be moved into the market expeditiously to get their benefits into public hands

quickly. Therefore, standards must be capable of qualifying novel technologies for reliable and durable performance under broad conditions of use. It is these comprehensive conditions of use that must be made to flow down to the storage system-level performance requirements.

Performance-based safety standards are based on criteria for onroad performance. They provide the opportunity for new technologies to qualify for onroad use -- a new design need not be held out of the marketplace waiting for a new prescriptive standard to be formalized. By analogy, crash-test requirements for vehicle crash safety are performance-based -- they apply to uniformly to all vehicles without differentiation for the materials used in a vehicle's structure, for its structural design, or for the techniques used in its manufacture.

This paper has two objectives:

The first is to assist the transition from historical prescriptive standards for gaseous fuel storage on vehicles to performance-based standards. Ideally, performance standards comprehensively identify stressful onroad conditions and require demonstration of safe performance under realistically compounded, worst-case exposure to those conditions. Highlights of how this approach can be applied to establish storage validation tests is presented herein using SAE J2579 as the example.

The second is to motivate a transition from reliance on virgin vessel burst pressure requirements as the safeguard against stress rupture and fatigue to more robust metrics for residual strength and stability throughout service life. Highlights of how this approach can be applied to establish appropriate validation

requirements for the design and production of gaseous storage are presented. Again, SAE J2579 is used as the example.

This is not a formal report from the SAE Fuel Cell Safety Work Group. But by using the contents of SAE J2579 as an example of data-based performance-based requirements, this paper indirectly provides substantiation for elements of J2579.

HISTORICAL PERSPECTIVE: CNG STORAGE

From a safety perspective, high pressure onboard hydrogen storage is the feature that most distinguishes fuel cell vehicles from conventional vehicles. High-voltage systems used in vehicle powertrains are already comprehended by safety requirements for hybrid-electric vehicles.

CNG vehicles provide a useful historical reference for gaseous storage. Perhaps surprisingly, storage standards for natural gas vehicles are not sufficiently general to handle all safety issues specific to hydrogen storage. Three aspects lead to unique safety considerations: 1) chemical and physical properties of hydrogen (e.g., Joule Thompson effect, permeability, and flammability), 2) higher pressures (greater than 30 MPa), and 3) broader operating conditions.

Standards for gaseous storage in natural gas vehicles can be seen as a list of tests that screen for onroad failures that have occurred in CNG tanks operating at less than 30 MPa. All of the recorded severe failures (rupture) pertained either to fire, to abuse/damage, to chemical exposure, or to the durability of metal and glass-fiber-composite tanks after extended static and cycling pressure. Each circumstance is addressed with one of the historical validation tests for CNG tanks, such as CSA-America's NGV2. Each test was designed and proven to reproduce a failure mechanism, and thereby replicate a failure that occurred in vehicle service. In several cases, the resulting requirements are prescriptive, rather than performance-based -- tests are applied differently for systems with different materials and/or construction design -- they target the specific failure mechanisms that have occurred with CNG tanks with historical materials/constructions operating at pressures under 30MPa. Hence, prescriptive requirements are reactive (reflecting past failures) rather than proactive (screening for future failures that may occur under different combinations of onroad conditions, new materials and new constructions). Performance-based standards do not assume failure mechanisms are known or that materials and constructions can be fully anticipated, but instead seek to comprehensively identify worst-case stressful onroad conditions to be managed by a road-worthy system. The breadth of conditions under which CNG metal and glass-fiber tanks failed when operated at pressures below 30MPa is not necessarily sufficient to encompass risk conditions for hydrogen systems made with new materials and constructions, and

operating at different working pressures and fueling conditions.

Another difference from the CNG history is the involvement of a broader community of experts early in the process of developing safety requirements. The early CNG community drew primarily on the expertise of pressure-vessel and component manufacturers, and after-market adapters of gasoline vehicles. The broader community engaged in development of hydrogen requirements for vehicles includes vehicle designers and manufacturers, who bring broader experience with onroad vehicle safety, who have experience with management of risk when a product is in use by a diverse population and in uncontrolled conditions. In addition, experts from the emerging fueling and repair/service infrastructures are engaged to coordinate requirements for fueling and de-fueling. And finally, component manufacturers are engaged to specifically coordinate requirements for component reliability, durability and performance so that those features will be consistent with the expected performance of safety for the storage systems into which they are incorporated.

MANAGEMENT OF RISK: Minimum Performance Criteria

The development of qualification tests and other specifications for hydrogen storage systems has been based on systematic risk management. Risk = (probability of an adverse event occurring) x (severity of an adverse event). So risk is managed by reducing the probability and/or severity of adverse events. The unintended release of fuel by leakage or rupture are the primary adverse events of concern with hydrogen storage systems on fuel cell vehicles.

Figure 1 illustrates the approach used in SAE J2579. The probability of an adverse event is given by the overlap of two probability distribution functions: the probability distribution for stressful conditions that occur in varying severities during service life, and the probability distribution for storage systems to leak/rupture when subjected to stressful onroad conditions. If the overlap is insignificant, then the risk is minimal.

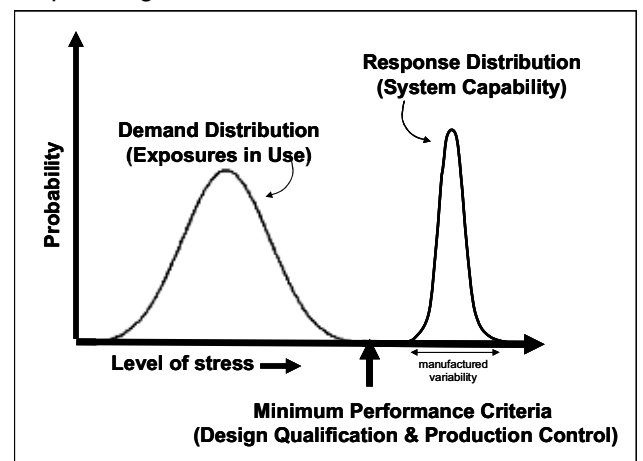


Figure 1. Management of Risk

The severity of stresses applied in validation testing is represented by the “minimum performance criteria” in Figure 1, which corresponds to severe stress conditions at or beyond the extreme for onroad lifetime service. Setting these criteria correctly – at worst-case extremes of onroad conditions – is the key to establishing robust design qualification tests.

The probability distribution for leakage is managed by design and production testing (e.g., SAE J2579) to verify that the storage systems can be expected to perform above the specified Minimum Performance Criteria for all anticipated extremes of expected service. The probability of vessel rupture is managed similarly, but with additional requirements for residual strength and stability at the end of service.

It is not enough for prototype designs to demonstrate their ability to sustain comprehensive onroad stresses. In addition, the production units must demonstrate tight correspondence to the capabilities of the validated design prototypes to assure that production units have the required performance capability.

Three features make qualification tests established in this manner more demanding than historical CNG vessel tests:

1. compounded stresses,
2. full system performance, and
3. comprehensive onroad stress conditions.

(1) refers to the application of onroad stresses simultaneously and/or in sequence. For example, in real-world onroad use, a vessel that is subjected to chemical exposures may also have been dropped during installation and could be in service for decades, and thereby experience a lifetime of fueling pressure cycles. So to verify onroad performance, these stresses must be applied to a single vessel, each in its worst-case extreme. This compounded test criteria is more severe than historical requirements where each stress is applied to a separate vessel. And it corresponds more closely to the extreme of real-world potential risk. In another example, internal temperature stresses exacerbated by the presence of hydrogen gas and extreme ambient temperatures during fueling/defueling are produced by the simultaneous application of these factors during testing.

(2) refers to the requirement that the full storage system (defined as all surfaces in direct contact with high pressure hydrogen in the storage vessel(s)) must demonstrate reliable containment of hydrogen without rupture or unacceptable leak. The key feature is that interfaces between components (e.g., shut off valves, check valves, pressure relief devices) and the storage tanks are validated as leak tight and not susceptible to blow-out during extremes of vehicle service. (In addition, components responsible for enclosure of high pressure hydrogen (shut off valves, check valves and PRDs) are

expected to be individually qualified for reliable and durable operation with high pressure hydrogen.)

And finally, (3) refers to a comprehensive evaluation of all anticipated sources of stress during service life, not just those that have been linked to failures of earlier tank designs or materials. Therefore, if new designs/materials/manufacturing processes are subject to failure mechanisms that differ from those seen in the past, the qualification testing is designed to assess performance where those failure mechanisms could occur in onroad service.

PERFORMANCE REQUIREMENTS: Qualification Testing

Performance standards designed to verify safety in onroad vehicle service need two elements:

- Qualification test protocols that produce worst-case stress conditions of service life
- Acceptance criteria

QUALIFICATION TEST PROTOCOLS -- In setting test conditions, awareness of historical failure mechanisms is helpful but not sufficient. Instead, a comprehensive approach to defining extreme conditions of onroad vehicle service is required. Storage systems must function under stresses of normal vehicle operation and under externally imposed stresses.

Externally Imposed Stresses -- Storage systems used in onroad vehicles can be expected to encounter four types of externally imposed stresses: impact (drop during installation, road wear and penetration), fire, fueling station malfunction (over-pressurization), and environmental exposures. For fire and penetration, the probability of unintended release cannot be reduced sufficiently, but the probability of rupture is reduced by the requirement to demonstrate release without rupture (discussed below). The remaining external factors, drop, road wear and environmental exposure (chemicals combined with temperature/humidity exposure), and fueling station malfunction (over-pressurization) can be aggressive assaults on the vessel structure, and hence present rupture risks. SAE J2579 provides an example of robust performance requirements that comprehensively address these externally imposed stresses. Requirements in Section 5.2.2.2 (“Durability (Hydraulic) Performance Test: Extreme Conditions and Extended Usage”) are illustrated in Figure 2.

Extreme Service Durability -- In SAE J2579, qualification for lifetime service requires a robust test of the durability of vessels to survive these events and to thereafter perform reliably through a service lifetime of extreme use. Since a vessel dropped during installation would thereafter be exposed to road wear (e.g., stone chips, abrasion from vessel bindings) and to environmental factors, the application of these stresses in series is required. The worst-case factors to be applied are

drop from maximum fork-lift height, concentrated application of chemicals to punctures through external coatings with refreshed exposure throughout 48 hours of high humidity with the system at full pressure, followed by a demonstration of the capability to sustain fueling pressure cycles through extremely lengthy service.

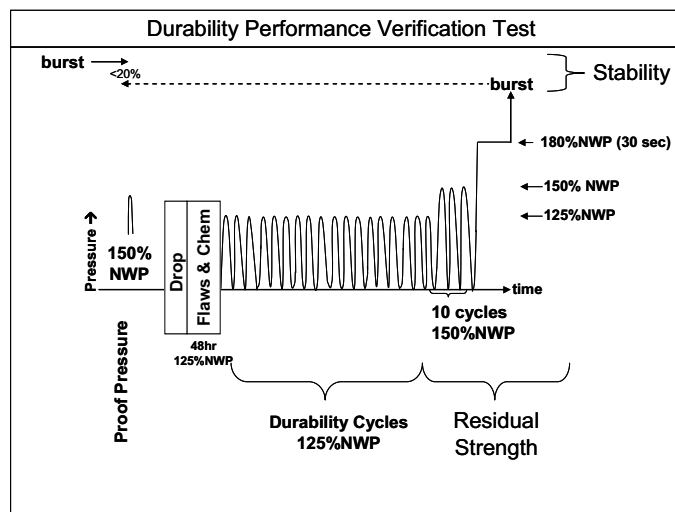


Figure 2.
Durability Performance Test in SAE 2579 (2008)

Surveys of vehicle service¹ show the extreme lifetime miles to be ~366k. Since passenger vehicles currently exceed 200 miles of travel with a full fuel tank; $366k/200=1830$ exceeds the number of full fuelings in current vehicles. As an added assurance of residual strength for rupture prevention, consideration of additional numbers of fuelings in the likelihood of partial fillings is accommodated in the qualification testing by considering a lifetime of fuelings at only 1/3 capacity, thereby requiring $3 \times 1830 \sim 5500$ pressure cycles to 125%NWP; this is beyond worst-case since partial fuelings have been shown to exert considerably less stress than 2MPa-to-125%NWP fuelings. As a corroboration, it has been shown² that a six-sigma projection ($\sim 10^{-9}$ probability) from the distribution of recorded lifetime vehicle miles traveled¹ would also support ~5500 pressure cycles as the statistically extreme worst-case. These pressure cycles, which serve to accelerate the fatigue of vessel wrap material, can be applied either pneumatically or hydraulically.

Requirements for fueling stations have been established (CSA and ISO have standards under development) that limit the fueling pressure to 125%NWP and require monitoring/intervention to limit a potential over-pressurization to <150%NWP. As a worst case, exposure to this over-pressurization is assumed to occur at the end of service life. Therefore, survival of 10 fueling station failures at the end of life is a new performance qualification requirement of SAE J2579.

Expected Vehicle Operations -- SAE J2579 provides an example of robust performance requirements that comprehensively address expected vehicle operations.

Requirements in Section 5.2.2.1 (“Expected Service (Pneumatic) Performance Test”) are illustrated in Figure 3. Systems are subjected to a high incidence of expected worst-case conditions and are required to perform without rupture or unacceptable leak/permeation. In addition, they must demonstrate residual strength after lifetime-equivalent durations of exposure to extreme stresses of vehicle service.

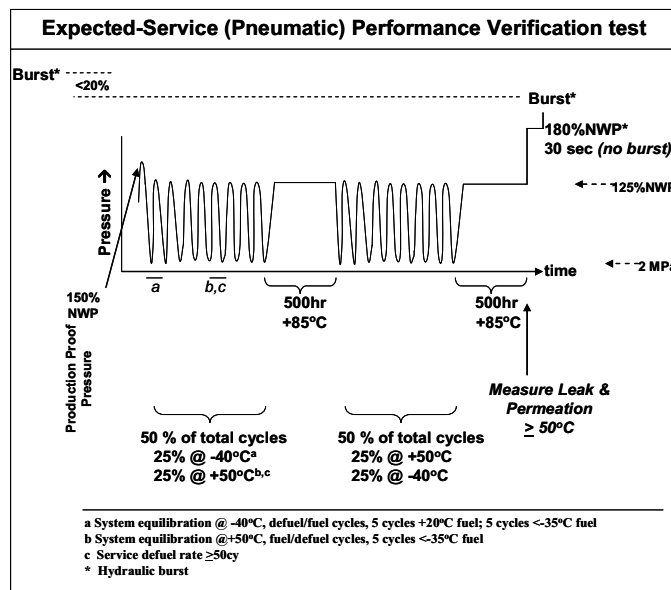


Figure 3.
Expected Service Performance Test in SAE 2579
(2008)

Expected vehicle operations include fueling, parking, and driving. In each case, stress is applied internally by high pressure hydrogen. Performance must be demonstrated with hydrogen gas because the unique properties of hydrogen can create additional internally imposed stresses. For example, because hydrogen is a small molecule, pressure changes may drive greater infusion-into/withdrawal-from interstices within materials and sealing interfaces than would occur with larger molecules, like natural gas. The combination of stress factors that occur in normal operation could promote previously unrecognized failure mechanisms (e.g., temperature-amplified, hydrogen-induced embrittlement of metals, or contraction and rigidity in sealing materials) that should be elicited in qualification testing rather than onroad service. Therefore, qualification testing must include compounded and realistic extreme conditions of fueling, parking and defueling (driving) with hydrogen.

Fueling / defueling (driving) performance requirement --
The following features are key to achieving comprehensiveness with regard to the stressful fueling/defueling conditions that are tested:

- rate of internal pressure change.

Maximum temperature and pressure shock occur with rapid fueling and defueling, so rapid 3-minute