STP/PT-003

HYDROGEN STANDARDIZATION INTERIM REPORT

For
Tanks, Piping, and Pipelines

ASME STANDARDS
TECHNOLOGY, LLC

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FOREWORD

Commercialization of fuel cells, in particular fuel cell vehicles, will require development of an extensive hydrogen infrastructure comparable to that which exists today for petroleum. This infrastructure must include the means to safely and efficiently generate, transport, distribute, store, and use hydrogen as a fuel. Standardization of pressure retaining components, such as tanks, piping, and pipelines, will enable hydrogen infrastructure development by establishing confidence in the technical integrity of products.

Since 1884, the American Society of Mechanical Engineers (ASME) has been developing codes and standards (C&S) that protect public health and safety. The traditional approach to standards development involved writing prescriptive standards only after technology has been established and commercialized. With the push toward a hydrogen economy, government and industry have realized that they cannot afford a hydrogen-related safety incident that may undermine consumer confidence. As a result, ASME has adopted a more anticipatory approach to standardization for hydrogen infrastructure which involves writing standards with more performance based requirements in parallel with technology development and before commercialization has begun.

Today, ASME codes and standards are used for hydrogen storage, transmission, and distribution. The anticipated requirements of the hydrogen economy will require local refueling stations with the capability to fill gaseous hydrogen vehicle tanks rapidly, to pressures as high as 10,000 psig. Although current standards could be used to build pressure vessels, piping, and pipelines meeting these operating requirements, it is likely that the resulting components would not, as a practical matter, enable commercialization of the technology.

ASME has worked closely with the Department of Energy (DOE), national laboratories, and other standards developing organizations (SDOs) to identify lead organizations to address the need for standards for hydrogen applications. ASME was selected to lead the efforts for pressure vessels, piping, and pipelines for storage, transportation, and distribution of hydrogen. Initial work of the ASME's Hydrogen Steering Committee led to the formation of volunteer task forces under the ASME Board on Pressure Technology Codes and Standards (BPTCS) to explore the standardization requirements for storage tanks, transportation tanks, portable tanks, piping, and pipelines for hydrogen-specific applications. The task forces submitted their recommendations at the end of 2003, and these recommendations led to initiation of standards actions, formation of project teams, and commencement of supporting research.

The ASME Boiler and Pressure Vessel (BPV) Standards Committee appointed a project team to develop new Code rules in the Boiler and Pressure Vessel Code Section VIII (pressure vessels) and Section XII (transport tanks) for hydrogen storage and transport tanks to be used in the storage and transport of liquid and gaseous hydrogen and metal hydrides. Rules for gaseous storage vessels with maximum allowable working pressures (MAWPs) up to 15,000 psig will be needed. Research activities are being coordinated to develop data and technical reports concurrent with standards development and have been prioritized per Project Team needs. The Project Team may identify additional needs and gaps as drafts are developed.

The Technical Reports to be developed will establish data and other information to be used to support and facilitate separate initiatives to develop ASME standards for the hydrogen infrastructure. These reports will target specific disciplines and fill the gaps identified by ASME's hydrogen task forces. This report is the first in a series of technical reports to be developed under sponsorship from the National Renewable Energy Laboratory (NREL) and addressing the following priority hydrogen infrastructure applications:

(a) H_2 Storage Tanks

(b) H_2 Transport Tanks

(c) H_2 Piping and Pipelines

(d) Portable H_2 Tanks

The H_2 Standardization Interim Report is intended to address priority topical areas within each of the four pressure technology applications for hydrogen infrastructure development. The planned application-specific reports will adopt the applicable sections of the interim report and further address key standardization issues including, as applicable, materials, design, fabrication, testing, examination, inspection, operation, maintenance, and installation. The application-specific reports are expected to serve as a primary reference for standards committees for review and approval of the draft standards.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a 120,000 member professional not-for-profit organization focused on technical, educational, and research issues of the engineering and technology community. ASME conducts one of the world's largest technical publishing operations, holds numerous technical conferences worldwide, and offers hundreds of professional development courses each year. ASME maintains and distributes 600 codes and standards used around the world for the design, manufacturing and installation of mechanical devices. Visit www.asme.org for more information.

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ABSTRACT

This interim report is intended to address priority topical areas within pressure technology applications for hydrogen infrastructure development. The scope of this interim report includes addressing standardization issues related storage tanks, transportation tanks, portable tanks, and piping and pipelines. It is anticipated that the contents and recommendation of this report may be revised as further research and development becomes available.

The scope for the tank portions of this report (Parts I and II) includes review of existing standards, comparison with ASME Boiler and Pressure Vessel Code (BPVC) Section VIII, and recommendations for appropriate design requirements applicable to small and large vessels for high strength applications up to 15,000 psi. This report also includes identification of design, manufacturing, and testing issues related to use of existing pressure vessel standards for high strength applications up to 15,000 psi, identification of commonly used materials, and developing data for successful service experience of vessels in H_2 service.

Similarly, the scope of piping and pipelines portion of this report (Part III) includes reviewing existing codes and standards, recommending appropriate design margins and rules for pressure design up to 15,000 psi, reviewing the effects of H_2 on commonly used materials, developing data for successful service experience, researching leak tightness performance, investigating effects of surface condition of piping components, and investigating piping/tubing bending issues.

Part I - H_2 Tanks: Review of Existing Reference Standards

The study provides a detailed overview of various compressed gas cylinder standards in comparison to ASME Section VIII rules with particular emphasis on the differing design burst margins and the modifications required to make the rules applicable to high-strength metal or composite vessels for both stationary and transport uses at pressures up to 15,000 psi.

The margins between burst and maximum operating pressure for common transport compressed gas cylinders and vehicle fuel containers were found to be very similar to one another and also very similar to the basic design margin of ASME Section VIII Division 3 vessels. The minimum margin found was for the U.S. Department of Transportation (DOT) DOT-3AA specification, and this margin is recommended as the minimum for future design rules. The various metal cylinder design formulas were found to deviate significantly from the burst prediction formula as pressures were increased to 15,000 psi and the ASME Section VIII Division 3 collapse formula is recommended for future rules at these high pressures. Low design margins for metal vessels were found to be dependent on associated periodic requalification and specific recommendations are included for all designs except the higher margin rules of ASME Section VIII Division 1 and ASME Section VIII Division 2. The standards do not presently provide adequate coverage of fatigue and fracture issues for 15,000 psi metal vessels in a hydrogen environment and the concerns are discussed in comparison to lower pressure experience. It should be noted that standards developed by different standards developing organizations utilize different consensus processes, may have different approaches, and are typically intended for different applications; therefore design margins and pressure definitions vary accordingly.

It was found that evaluation of composite gas cylinder margins must address time at various stress levels for time-dependent mechanisms such as stress rupture to control. The allowable stress for glass composites was determined to be very similar for all standards and the glass stress requirements of the DOT Fiber Reinforced Plastic (FRP) specifications are recommended as the initial basis for future rules. It should be noted that FRP-1, FRP-2, and CFFC are limited in scope, sizes, designs, and materials and these limitations, along with the operating experience of other standards, such as natural gas vehicle-2 (NGV-2), should also be considered for future rules. Generally, composite cylinders

were not found to be designed using consensus-based rules. A preliminary proposal was outlined whereby simplified design may be developed and verified for general application. The allowable stress and resulting burst margins for carbon composites were found to vary significantly among the standards, presenting no single value. The discussion includes the significant differences between the service conditions of stationary and transport vessels and this should facilitate study of the necessary allowable design stress for future carbon composite design rules. The various composite cylinder standards vary significantly with regard to required resistance to external damage from chemicals and impact, and significant gaps are identified. Specific recommendations are included for the development of nondestructive examination (NDE) techniques for composite requalification, and recommendations for a performance based approach for validation of new techniques for use on different designs are provided.

Part II - H_2 Tanks: Study of Existing Data, Standards, and Materials

This study evaluates the potential use of four metallic vessel standards [ASME VIII-1 Appendix 22, 49 Code of Federal Regulations (CFR) 178, American National Standards Institute (ANSI)/CSA NGV2-1], and International Organization for Standardization (ISO)/Draft International Standard (DIS) 15869-2, and six composite vessel standards (DOT FRP-1 and FRP-2, ANSI/CSA NGV2, ASME VIII-3 Code Case 2390, ISO 11119, and ISO/DIS 15869) for 15,000 psi hydrogen service.

The study identifies problems with using existing standards (1) for pressures well above current common practice and (2) for hydrogen with its material compatibility issues, flammability, and small molecular size. Design, manufacturing, and testing gaps are identified in existing standards, and recommendations are made for future standards dedicated to this challenging service.

Commonly used materials are rated for their resistance to hydrogen embrittlement and crack growth. Where test data are lacking, recommendations are made for future data collection. In-service inspections (ISIs) based on fracture mechanics, analyses are recommended, but cycle-to-failure tests (using hydrogen) and design life limits may be required until data are available.

Tables and figures are used to display successful service data for storage, transport, portable, and fuel tank service. All metal vessels have service histories of 60+ years, with composites gaining acceptance in the last 5 to 10 years (mostly in vehicle fuel tank applications). The successful service data support the reduction of design margins for some metallic vessels, and also support the "performance standard" concept for composite vessels.

Part III - H_2 Piping and Pipelines: Study of Existing Data, Standards, and Materials

This study evaluates the potential use of four piping and pipeline codes (ASME B31.1, 31.3, 31.8, and 49 CFR 192) for up to 15,000 psi hydrogen service.

The study compares the codes and determines the existing design margins. Tables and figures are provided to display the design margins, and also to display successful service data for piping systems and pipelines built in accordance with the codes. Some service data dates back to the 1940s.

Commonly used materials are rated for their resistance to hydrogen embrittlement and crack growth. A table is provided that lists recommended materials for high-pressure hydrogen service. For pipelines, reference to European Industrial Gases Association/Compressed Gas Association (EIGA/CGA) 121/04/E is recommended. For small piping systems, 316L stainless steel (SS) is recommended.

Several special topics related to hydrogen service are covered: performance of welded and mechanical joints, post-weld and post-formed heat treatment, effects of surface finish, and hot and cold pipe/tube bending.

Recommendations are provided for design margins for systems constructed of materials that are resistant to hydrogen embrittlement. Where less optimum materials are selected, the same design margins can be used with adequate initial and in-service inspections.

Recommendations are made for future standards dedicated to high-pressure hydrogen service. The design rule recommendations account for the challenges of (1) pressures well above current common practice and (2) hydrogen with its material compatibility issues, flammability, and small molecular size.

PART I - Review of Existing Reference Standards to Support New Code Rules for High-Pressure Hydrogen Vessels

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1 INTRODUCTION

1.1 General Background of Code Work for 15,000 psi Hydrogen Vessels

The ASME Boiler and Pressure Vessel Committee Project Team on Hydrogen Tanks has been formed to develop Code vessel rules for storage and transport of gaseous hydrogen at pressures up to 15,000 psi. There are now a relatively small number of hydrogen vessels and transport tanks in use at pressures as high as 10,000 psi. These vessels may not be suitable models for high volume usage as is expected for hydrogen as an alternative fuel. This report compares the requirements and commonly known experience base of a variety of standards for gas cylinders and pressure vessels used in common operating pressures between 2,000 and 5,000 psi. The standards considered cover a spectrum from the more prescriptive design approach of the ASME Section VIII Code to the performance based requirements of NGV2 for full composite cylinders.

The scope of this work is very broad, but limited in depth. There are often several potential remedies proposed for a single issue. This is the result of drawing on the diverse existing standards. In addition, the critical work of characterizing materials performance in 15,000-psi hydrogen has yet to be completed.

The reference standards, listed below in Section 1.2, also incorporate a variety of assumptions about the service conditions and periodic requalification needed to ensure continuing operational integrity. These differences are appropriate, but make it difficult to simply copy a standard intended for one type of service to another, different, type of service. An example is the difference in application and requalification between conventional individual DOT gas cylinders and vehicle fuel tanks. In the first instance the cylinder is exposed to a very broad range of potential physical damage in shipment and use, but the number of fatigue cycles is small and there is effectively unlimited access for inspection at requalification. In the second instance, the tank is installed in a protective vehicle structure, limiting the potential for physical damage but also limiting access for requalification. There are also a large number of fatigue cycles for fuel tanks. These differences in service conditions, absent any significant differences in gas or pressure contained, contribute to significantly different approaches to assure integrity.

This report attempts to present a listing of potential issues, often with recommendations to be considered by the committee responsible for the new rules. The broad safety issues of margins, fatigue, material compatibility, resistance to failure due to damage in service, requalification, and efficient design for 15,000 psi must be addressed in new rules, but there are many solutions that may be based on available data, some valid for only certain types of vessels and not for others. This report should provide an extensive kit of basic background, references, and tools that can be used as input to a good consensus standard development process. This report does not attempt to address all technical issues related to standards for hydrogen infrastructure applications, and it is expected that areas requiring further investigation will be identified.

There are also issues identified where no solution is available from the reference standards and available data. Although it is acknowledged that not all existing data was reviewed within the scope of this evaluation, it is generally concluded that hydrogen compatibility and fracture safety, both for thick metal vessels in fatigue and composite vessels after impact damage, are two examples of concerns that are not easily addressed by reference to traditional design controls and available data. These issues require solutions that are based on developed technology, verified to be effective and peer reviewed.

The recommendations are embedded with the relevant text sections. It is believed that the recommendations must be considered in the detailed context and not treated as a checklist that can be separated from the background discussion.

1.2 Reference Standards

The standards listed below were reviewed and compared in the preparation of this report.

ASME VIII-1
ASME VIII-2 App. 22
ASME VIII-2
ASME VIII-3
DOT FRP-1
DOT FRP-2
DOT CFFC
DOT-3AA
DOT-3AAX
IGC Document 100/03/E
ISO 9809-1
ISO 111120
ISO 11119
NGV2
ISO 11439
ISO 15869
ASME Code Case 2390

1.3 Steel Cylinder Designs

The typical transport tank is designed to DOT Specification DOT-3AAX with a water capacity of several thousand pounds and a fill pressure between 2,000 and 3,000 psi. The construction is from seamless low-alloy steel, typically quenched and tempered 4130x and has a relatively low margin. The common terminology for this tank is a trailer tube, and they are usually fixed to a frame on a semi trailer or in a separate ISO module configuration. Although the DOT-3AAX specification imposes no maximum pressure limit, it may not be practical to scale this design to the much higher pressures envisioned for hydrogen transport. The thickness of the sidewall must increase at least proportionally with the pressure increase, and the hardenability of the steel is believed inadequate for the resulting heavier sections.

Increasing the alloy content can improve the quench response but there is a second constraint, the provision of a leak-before-break (LBB) failure mode. The relatively low margins common to seamless gas cylinders are acceptable because the cylinders will typically not fail by rupture. The U.S. DOT has required consideration of LBB as part of all recent new high-pressure cylinder designs and this should be anticipated as a requirement for new hydrogen tanks. The existing exemptions and work performed in ISO TC58/SC3/WG14 and reported in ISO TR 12391-2 found that LBB could be achieved at thicknesses at least up to 14.4 mm (0.567 in.) in DOT-3AA design. LBB may be achieved at higher material thicknesses with high-strength material operating at high pressures. As the wall thickness is increased, it is expected that this may be compounded by the unfavorable effect of hydrogen exposure on the fracture toughness of the steel. It may be more difficult to achieve LBB performance due to materials limits on fracture toughness.

A third barrier to the use of the DOT-3AAX specification is the very high weight of these all-metal designs, compounded by the unfavorable wall thickness ratios due to thick wall effects and the unfavorable compressibility factor of hydrogen at 15,000 psi. Hydrogen transportation by truck is governed by the maximum gross weight regulations for highway use. Any change that increases the relative weight of vessels will reduce the payload. As an approximation, the weight of a given design type of vessel with fixed material properties is proportional to the product of water volume and design pressure. If the pressure or volume is doubled, the weight is also doubled.

A rough approximation of the effect on vessel weight resulting from increasing the operating pressure was calculated by extrapolation of the hydrogen compressibility factor based on a published chart [64] covering the range of 0 to 6,000 psia. The factor is not exactly linear, showing slight upward inflection, but the approximation will serve. The estimated compressibility factor is 1.10 at the conventional service pressure of current transport vessels, 2,640 psi. At 15,000 psi the approximate compressibility factor is at least 3.15 and probably somewhat greater; however, additional investigation may be required to confirm the extrapolation. The amount of gas stored in a vessel of given size is the product of the water volume times the pressure ratio, fill pressure divided by atmospheric and then divided by the compressibility factor. If the weight of a vessel is assumed to increase linearly with design pressure, the payload of a truck using DOT-3AAX 15,000-psi vessels would be reduced by the compressibility factor ratio, 1.1:3.15 or a 65% reduction in payload at the maximum weight limit. Looked at another way, the weight of the vessel design must be reduced by the same factor to maintain the current payload. This magnitude of weight reduction is unlikely using any metals but may be feasible with composites.

Usually DOT gas cylinders are not at risk for fatigue failure in service. With few exceptions such as breathing apparatus cylinders, these cylinders are used as shipping containers and the number of pressure cycles per year is low compared to the typical fatigue cycle life of at least 10,000 cycles up to an effectively infinite fatigue life. It is expected that exposure to hydrogen at high pressures will reduce the fatigue life by a significant margin [1].

DOT specifications apply limits to the sidewall thickness as a function of material strength, but do not contain design rules for the ends. DOT also restricts discontinuities such as openings in the sidewall but not in the ends. ISO 9809 does add design constraints for the ends, but these features must still be proven by prototype test. Since the burst margin depends on the sidewall in these cylinders, it is appropriate to consider these design standards for the purposes of margins between burst pressure and operating pressure.

The DOT specification also effectively prohibits the use of autofrettage to improve the stress distribution at operating pressure by prohibiting the application of high internal pressures prior to the hydrostatic expansion test. This requirement is inherent in the design strategy for DOT cylinders as discussed later, but is a disadvantage at very high pressures.

The combined effects of hydrogen degradation of steel materials and thick-wall effects of 15,000 psi vessels introduces issues requiring new material data and possibly new design or NDE techniques in the development of new design rules. The inherent high weight of metal designs, even with the lowest proven margins, is also likely to be a limiting factor in their use for transportation at 15,000 psi.

1.4 Composite Cylinder Designs

Composite reinforced designs offer more weight-efficient transportation tanks but there is currently no specification or standard for such tanks at 15,000 psi. The properties and manufacturing of composites can address the critical concerns for metal vessels because metal liner sections can be thinner, LBB is easier to achieve at high pressures, depending upon the details of construction, and fatigue is therefore less of a concern.

Smaller, lower pressure, composite tanks are produced under exemptions and to detailed designs proprietary to each manufacturer. The DOT, ISO and ANSI existing standards for smaller composite tanks are not harmonized and contain a variety of design margin requirements. The U.S. regulatory authority for cylinders used in the commercial transport of gases, DOT, has not accepted any standard as adequate for large composite vessels in high-pressure hydrogen, or any other industrial gas, service. The development of ASME Code rules specifically for such tanks using the ASME consensus process, presents the best case for a comprehensive and credible standard for such tanks.

1.5 Stationary Storage Vessels

Vehicle refueling infrastructures for gaseous fuels typically incorporate high-pressure storage vessels as receivers, buffer tanks, and cascade storage banks associated with compressor stations. In the absence of compressors, these vessels must operate at pressures greater than the refueling pressure of the vehicles, generally a minimum of 1.5 times the service pressure of the vehicle tank. With plans for 10,000-psi vehicle tanks, the storage vessels must be capable of 15,000 psi operating pressure.

Another consideration is the expansive heating effects of hydrogen, which would also require a higher tank fill pressure in order to achieve 10,000 psi upon cooling to ambient.

Using the CNG precedent, either ASME Section VIII vessels or DOT specification gas cylinders may be installed at compressor stations. This use is clearly within the scope of the ASME Code, but also clearly not within the scope of DOT regulations for the transportation of hazardous materials. Long and successful precedent in this and other non-transportation uses of DOT cylinders has resulted in references in other codes, notably National Fire Protection Association (NFPA) 52.

Code storage vessels for vehicle fuels are typically ASME Section VIII Division 1 forged vessels made in accordance with Appendix 22. The Appendix 22 vessels are identical in appearance to DOT trailer tubes and made from essentially the same alloy but with higher margins than required by DOT-3AAX. Scaling either of the present ASME designs to 15,000 psi encounters the same feasibility concerns as scaling the DOT trailer tubes except that weight is not as great an issue for the stationary ASME vessels and LBB may not be as firm a regulatory requirement. Additionally, ASME and DOT toughness rules differ.

ASME Section VIII Division 3 provides Code rules for efficient pressure vessels for higher pressures. The provision for prestressed designs, using autofrettage or other techniques, allows some of the thick wall adverse effects to be offset and the use of layered and prestressed designs allows for greater total wall thickness. LBB can also be achieved even in very thick vessels if they are layered and designed in accordance with KD-810 (f). These rules may be usable for ground storage vessels, but the resulting weight will probably still be too great for transport tanks. It should be noted that vessels could also be constructed to ASME Section VIII Divisions 1 and 2; however, Division 3 may be the most appropriate choice.

Code Case 2390 under Section VIII Division 3 allows a composite reinforced vessel to be constructed by hoop wrapping a steel liner with fiberglass composite but limits the design pressure to 3625 psi. Vessels of this type can be considered similar to wire wound vessels.

1.6 Performance Based vs. Prescriptive Standards

Generally, a performance based standard will state the goals and objectives along with methods (e.g., testing and inspection) to demonstrate whether the vessel meets these goals and objectives. A performance based standard will focus on the critical characteristics of the final vessel, rather than the specific processes used to produce it. In contrast, a prescriptive standard will typically specify materials, design, and construction rules, without stating the goals and objectives. It is anticipated that standards for hydrogen infrastructure will include a mixture of performance and prescriptive requirements.

ASME Code rules are predominantly engineering calculations based on thoroughly developed and accepted formulas or design by analysis for metal structures. These rules, though often complex, can be used, understood, discussed, and accepted by a large number of professionals. In contrast, the reference performance standards give little if any guidance in engineering calculation, relying entirely upon the engineer to devise a design that will reliably satisfy the stated performance requirements. Designers of composite vessels are particularly dependent on internally developed and proprietary design tools, as well as commercially available analysis programs. Finite element analysis is becoming more common, but there is no standardization required in the many assumptions made in the use of this technique.

1.7 Reference Performance Based Standards

The reference standards are predominantly performance based rather than design based in contrast to typical Code rules. These performance based standards have been largely successful in lowering the