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UNRAVELLING THE HYDROGEN REGULATORY FRAMEWORK: APPROVAL PROCESS FOR TYPE IV ONBOARD VEHICLE HYDROGEN FUEL CONTAINERS

R PEMBERTON, S GIANNIS

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R Pemberton, S Giannis
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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by
Dr Fernando Castro, Department of Engineering Head of Science.

Executive Summary

The report presents a comprehensive and easy to follow map of the existing regulatory framework for type-approval of Type IV hydrogen storage containers. The key regulations, (design) codes and standards relevant for onboard storage of hydrogen fuel in vehicles have been identified, and process maps detailing the stages within the approval process provided, demonstrating clear links between regulations and standards. Moreover, a gap analysis of the regulatory framework as well as a series of interviews with several UK stakeholders were conducted and opportunities for improvements in the approval process identified and explicitly described here. The key recommended activities are broadly classified into four groups: (A) Material and Component Testing, (B) Manufacturing, (C) Non-destructive Evaluation and (D) Structural Health Monitoring.

Contents

1 Introduction

Ambitious commitments to reach net zero emissions are being set globally. Policies such as the UK's Energy White Paper [1] and the European Green Deal [2] highlight the bold steps governments are taking to tackle climate change. In the UK, transport accounts for 28% of all greenhouse gas emissions, the biggest contributor of any sector [3]. Significant action is required to decarbonise the industry, with a major focus on accelerating the shift to zero emission vehicles.

Fuel cell electric vehicles (FCEVs) running on non-emitting hydrogen fuel present a potential technology route. The surge in lithium-ion battery production over the last decade and resultant cost reductions have led to the alternative option of electric vehicles (EVs) becoming a more commercially viable choice for light-duty vehicles such as passenger cars. FCEVs powered by hydrogen fuel have however retained interest as an option for medium and heavy-duty vehicles including trucks and buses. This is predominantly due the higher energy to weight ratios achieved compared to batteries, which becomes an important issue for larger vehicle types. This feature has meant hydrogen has also seen interest as a replacement fuel for other areas of the transport sector such as trains, aerospace, and shipping.

Several technologies exist to store hydrogen fuel on-board vehicles with storage as compressed gas in pressure vessels being the most widely adopted approach. Due to potential catastrophic failures from the combination of fuel, air and ignition sources, as well as high pressures and electrical hazards, hydrogen in compressed gaseous form presents several considerations from a safety perspective [4]. Regulatory frameworks are an essential feature to ensure risks associated with hydrogen storage systems are alleviated and public safety is upheld. A lack of awareness of the regulatory framework and difficultly navigating regulations, codes and standards (RCS) required for type-approval of hydrogen storage pressure vessels is seen as a significant barrier preventing potential market entrants and the development of supply chains to design, build, test and certify hydrogen storage pressure vessels. Much of the focus for gaseous hydrogen storage in vehicles has looked to use so called Type IV containers that utilise the high specific stiffness and strength of fibre-reinforced composites, a material class that also has evidenced barriers to uptake due to regulatory constraints [5, 6].

This document examines the existing regulatory framework for type-approval of fully composite Type IV hydrogen storage containers. Key regulations, (design) codes and standards relevant for on-board storage of hydrogen fuel in vehicles have been identified, and process maps detailing the stages within the approval process provided, showing links between RCS. In addition, a series of interviews with several UK stakeholders were conducted to assess opportunities for improvement associated with the approval process. Future collaborative research activities are suggested that could help overcome hurdles facilitating potential market entrants to start manufacturing hydrogen storage containers and the development of a UK supply chain.

2 Hydrogen Storage

Hydrogen Storage Technologies

When used as on-board fuel for transport and vehicle applications, appropriate systems for storing hydrogen are required. Storage systems need to be safe, cost effective, provide quick uptake and release of fuel and ideally operate at practical temperatures and pressures. Importantly for transport applications, storage needs to provide the required volumetric and gravimetric energy densities to minimise vehicle weight and reduce physical space required to store fuel within the vehicle [7].

Hydrogen storage technologies developed include physical-based and material-based systems [8] (Figure 2-1). Some examples of material-based technologies include storage within metal organic frameworks [9, 10, 11, 12], metal hydrides [13, 14], metal borohydrides [15, 16], carbon nanotubes [17, 18], kubas-type hydrogen storage [19], liquid organic hydrogen carriers [20], alongside chemically storing hydrogen in methane [21, 22] or ammonia [23, 24]. At present, material-based hydrogen storage technologies suffer considerable drawbacks including the requirement for thermal management systems, expensive catalysts, stability issues, slow kinetics, insufficient energy densities and safety concerns [7].

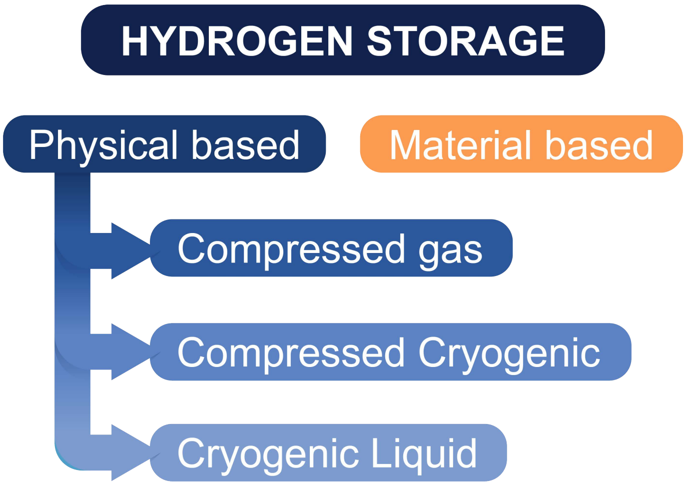
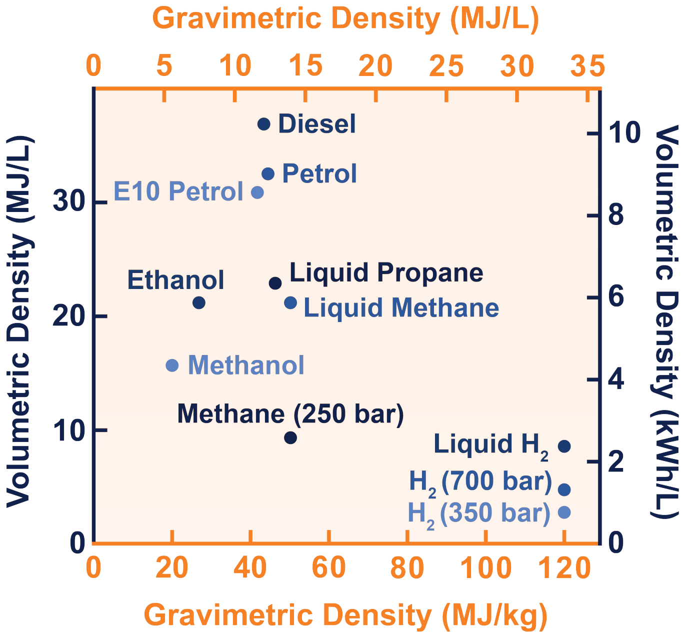


Figure 2-1 Types of hydrogen storage

As a result, the primary method for storing hydrogen for vehicle applications to date has been through physical-based technologies. These include storing hydrogen in the form of a compressed gas, cryogenic liquid or combined cryogenic compression in containers or pressure vessels [7, 8]. Storage of hydrogen as a gas requires high-pressure tanks (350 – 700 bar tank pressure), while storage of hydrogen as a liquid requires cryogenic temperatures as the boiling point of hydrogen at one atmosphere pressure is −252.8°C.

Fuel-cell powered vehicles require enough hydrogen to provide a driving range of more than 300 miles with the ability to refuel the vehicle quickly, and to meet this range for a number of light-duty vehicle platforms, an onboard hydrogen storage capacity of 5-13 kg will be needed. While hydrogen has nearly three times the energy content of gasoline on a mass basis, on a volume basis the situation is reversed, as shown in Figure 2-2, and this needs to be carefully factored into the chosen storage solution.



Due to the relatively low cost, maturity and ease of operation [25, 26, 27], storage of hydrogen as a compressed gas within pressure vessels has been the current industry preference for vehicle and transport applications.

Figure 2-2 Comparison of specific energy (energy per mass or gravimetric density) and energy density (energy per volume or volumetric density) for several fuels.

Types of Pressure Vessels

Pressure vessels for storing compressed gaseous hydrogen are classified according to the following types:

- Type I – Fully metallic
- Type II – Metallic liner reinforced with composite overwrap in hoop direction
- Type III – Metallic liner reinforced with fully composite overwrap
- Type IV – Polymer liner reinforced with fully composite overwrap
- Type V – Fully composite overwrap without liner

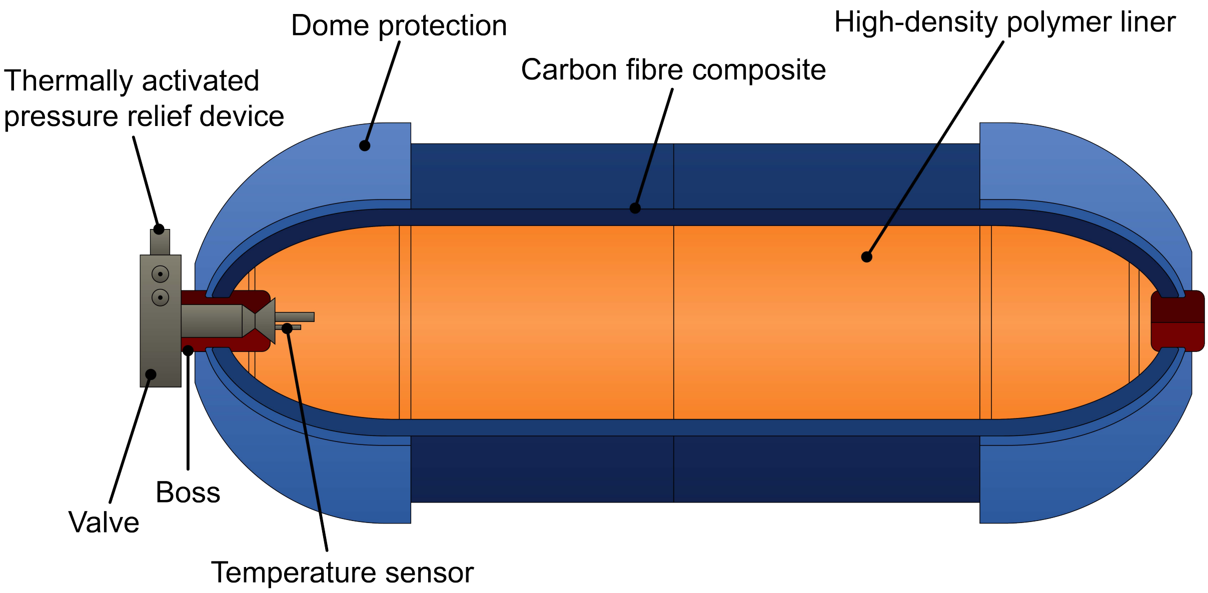


Figure 2-3 Typical Type IV hydrogen storage pressure vessel

To provide the required volumetric energy density for vehicle applications, gaseous hydrogen needs to be stored at high pressure, with typical nominal working pressures of containers between 350–700 bar. To achieve the volumetric energy densities required for storing hydrogen within a practical volume for transport applications, compressing the gas at the top end pressure of 700 bar is preferred.

The high pressures involved place emphasis on using structurally resilient pressure vessels with cylindrical Type III and IV containers, i.e. those incorporating the high strength- and stiffness-to-weight ratios gained from fully composite overwraps, preferred [28]. Alongside high fatigue resistance and corrosion resistance, the additional light-weighting received from the polymer liner in Type IV containers makes them an ideal solution for on-board storage in transport applications. The use of polymer liners also avoids issues specific to metals including susceptibility to hydrogen embrittlement [29].

Type IV Pressure Vessels

The base design of a Type IV container (Figure 2-3) consists of a non-structural polymer liner such as high-density polyethylene (HDPE) overwrapped with a fibre-reinforced polymer composite. The liner prevents gas leakage and permeation while the outer composite layer provides structural integrity [30]. An impact resistant foam or resin end dome is incorporated to provide protection to impact. Connection to the fuelling system is achieved through a threaded port in a metallic boss at one end of the container, typically made of anodized aluminium for corrosion prevention. For refuelling, hydrogen enters the container through a check valve preventing back-flow into the fuelling line. An automated shut-off valve prevents out-flow of stored hydrogen when the container is idle or not in operation. Containers also incorporate thermally activated pressure relief devices (TPRDs) that enable controlled release of gas from the container in the event of a fire to prevent hazardous rupture [4].

3 Approval Process for Type IV Onboard Vehicle Hydrogen Storage

A robust regulatory framework is an essential requirement to ensure public safety and alleviate risks associated with hydrogen storage in transport applications. Moreover, the regulatory framework underpins efficiency and sustainability in the life cycle of the product. The basis of such a framework consists of high-quality technical Regulations, Codes and Standards (RCS) that underpin rigorous approval and certification processes.

In a simplified way the hierarchy of the regulatory framework of any country can be visually presented as a pyramid consisting of three main sections. The top of the regulatory hierarchy is occupied by legally binding legislative acts. They can be in the form of *Regulations*, *Code of Regulations*, *Directives* or *Acts* developed through national administrative processes or international agreement. Their principal aim is to protect public safety and ensure sustainability. Documents (*codes*) e.g. for built environment and safety that are adopted by governmental bodies occupy the middle segment of the pyramid. A code is typically a model, a set of rules that define *what* needs to be done. Standards are the foundations of the pyramid and support the deployment of legislative acts by providing specific technical guidelines for design, manufacture and testing alongside setting minimum component performance requirements. In effect, standards define *how* things should be done. Unless explicitly mentioned in a legislative act, codes and standards are voluntary compliance documents and not legally binding. A more detailed discussion, including explanation of the role of regulatory authorities and standardisation organisations involved internationally with hydrogen technologies, can be found in [31].

RCS for On-Board Hydrogen Storage Technologies

There has been extensive activity developing RCS in support of systems and devices across production, storage, transportation, measurement and use of hydrogen. The following legislative acts are those pertinent for on-board hydrogen storage in vehicles:

Regulations

Regulation (EC) No. 79/2009 [32] – On type-approval of hydrogen-powered motor vehicles (and amending Directive 2007/46/EC [33])

Regulation 134 (UN/ECE) [34] – Uniform provisions concerning the approval of motor vehicles and their components with regard to safety-related performance of hydrogen-fuelled vehicles (HFCV)

Global Technical Regulation No. 13 (UN/GTR) [4] – On hydrogen and fuel cell vehicles

The now repealed Directive 2007/46 [33] has been replaced with Regulation (EU) 2018/858 [34]. This Regulation sets the general framework within the European Union (EU) for the type-approval and market surveillance of vehicles across different classes including passenger cars, buses, trucks, trailers alongside systems and components intended for such vehicles. Regulation (EC) No. 79/2009 [32] extends the provisions of (EU) 2018/858 for the specific case of hydrogen-powered vehicles detailing general requirements, technical specifications, and test procedures for type-approval of hydrogen systems and components [36].

Alongside this Regulation, to receive type-approval vehicles must comply with several separate technical Directives, such as UN/ECE Regulation 134 [34]. The World Forum for Harmonization of Vehicle Regulations and the European Commission (EC) are currently working on the harmonization between UN Regulations and EU Directives. Currently, some of the EU Directives are technically equivalent to UN Regulations or only refer to the requirements of the corresponding UN Regulation. The UN Global Technical Regulation No. 13 [4] is a technical Regulation but does not refer to a type-approval or certification procedure as mentioned in the EU Directives or UN Regulations. The UN

Regulations are considered candidates for the elaboration of UN Global Technical Regulations.

Within the UK the Vehicle Certification Agency (VCA), part of the Department for Transport (DfT), is the only entity that can certify and grant type-approval for Type IV containers. The VCA has the power to appoint Technical Services Laboratories to witness type-approval tests and collect evidence for submission to them as Competent Authorities when they have insufficient resources to undertake witness themselves.

Whilst there is an abundance of standards in existence concerning compressed gas storage in pressure vessels, the following are specific to those relating to on-board hydrogen storage for use in vehicles:

Standards

ISO 19881:2018 [37] Gaseous hydrogen – Land vehicle fuel containers

ANSI/HGV 2-2014 [38] Compressed hydrogen gas vehicle fuel containers

SAE J2579 2018 [39] Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

Global standardisation and harmonisation of standards for critical components of hydrogen storage systems for on-board hydrogen fuelled vehicles has been led by ISO Technical Committee 197 (ISO/TC 197 – Hydrogen Technologies). Within the responsibility of this technical committee includes ISO 19881:2018 [37] which details requirements for the materials, design, manufacture, marking and testing of containers intended only for the storage of compressed hydrogen gas as fuel for vehicle applications. The standard was developed based on ANSI/HGV-2 [38] and has been developed with direct reference to the requirements for type-approval stipulated in EC Regulation No. 79/2009 [32] and UN/ECE Regulation 134 [34].

Standards concerning specific design guidance for Type IV containers, e.g. ISO/TR 13086 series [40, 41, 42, 43] as well as construction and testing, e.g. ISO 11119 series [44] are also key documents for reference. These however are not necessarily exclusive to container design for compressed gaseous hydrogen storage as fuel on board a vehicle.

Approval Process for Type IV Containers

The general approval process highlighting the predominant stages for certifying Type IV containers is set out in Figure 4-1. This process has been diagrammatically shown using standard process flowcharts based on the RCS detailed within the previous section of this report, notably the requirements prescribed within ISO 19881:2018. In-depth process flows outlining the requirements of the individual approval stages and highlighting the links between regulations and standards are detailed in Appendix A – Detailed Approval Processes.

In conjunction with several stakeholders (incl. the National Composites Centre (NCC), the Vehicle Certification Authority (VCA), Luxfer Gas Cylinders and Hydrogen Europe) aspects of the approval process have been assessed for potential gaps and opportunities for improvement to enable a more robust future container certification process. This has included research and development opportunities to produce guidance to support the standards already in place, alongside reviewing aspects of the existing documentary standards. The outputs of the gap analysis are also presented in Figure 4-1 while the opportunities for interventions are listed in Table 4-1.

4 Recommendations

The key recommendations to further improve the approval process of Type IV onboard vehicle hydrogen fuel storage containers are presented in Table 4-1 as part of the approval process. These also broadly fall into four groups: (A) Material and Component Testing, (B) Manufacturing, (C) Non-destructive Evaluation and (D) Structural Health Monitoring.

The recommendations related to enhancements on aspects of material and component testing could be classified as short-term and be implemented within the next 12 months, following close cooperation with the relevant stakeholders.

The remaining suggested improvements (categories B, C & D) would require considerable R&D activities, involving both stakeholders from the materials and applications landscape, to develop the appropriate measurement technologies and solutions before producing the required guidance.

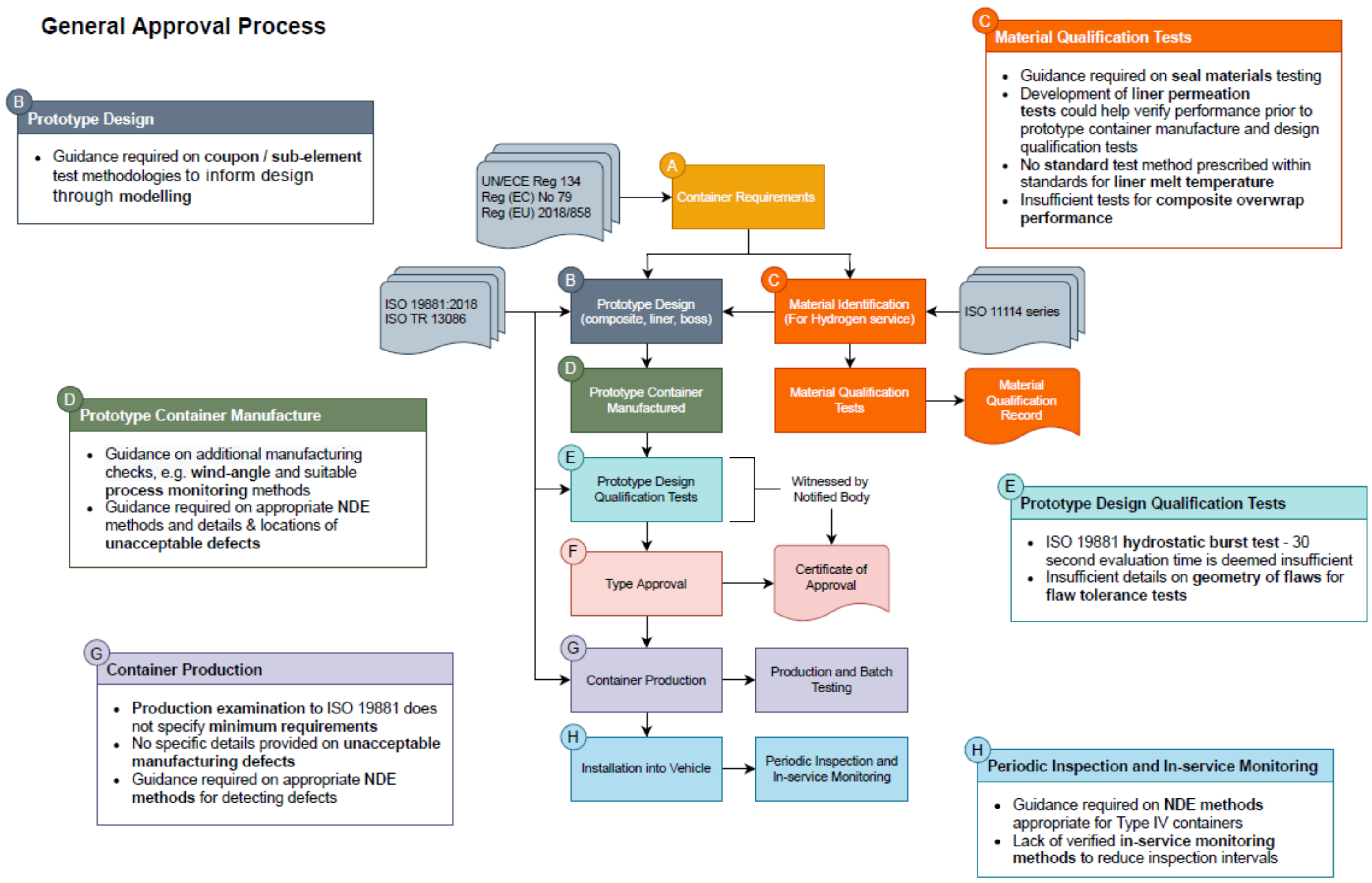


Figure 4-1 General Approval Process in accordance with ISO 19881:2018 and gap analysis

Table 4-1 Opportunities for improvements in the approval process for Type IV compressed hydrogen gas fuel containers

Approval Stage	Area	Suggested Improvements	
Prototype Design	Material data & coupon testing	Develop guidance on coupon / sub-element test methodologies to inform design through modelling	**A**
Material Qualification	Material tests	Specify requirements and develop guidance on seal materials testing	**A**
	Liner	Include permeation tests to verify performance prior to prototype container manufacture and qualification tests	**A**
	Melt temperature	Include recommended standard for melt temperature testing (e.g. ISO 3146:2000)	**A**
	Composite overwrap	Include recommendations for further testing of composite overwrap material (e.g. tensile testing to ISO 527)	**A**
Prototype Container Manufacture	Composite filament winding and curing	Develop guidance on additional manufacturing quality checks and suitable process monitoring methods	**B**
	Non-destructive evaluation (NDE)	Develop guidance on appropriate NDE methods and details & locations of unacceptable defects	**C**
Prototype Design Qualification Tests	Hydrostatic burst	Review and validate the suggested time to evaluate performance of a container during hydrostatic burst	**A**
	Flaw tolerance	Provide further details on geometry of flaws for flaw tolerance tests	**B/C**
Container Production	Production testing and inspection	Develop guidance on minimum requirements for production examination	**C**
	Flaws	Specify in detail the nature and effect of unacceptable manufacturing defects	**B/C**
	Defect detection	Provide guidance on appropriate NDE methods for defecting defects	**C**
Installation into Vehicle	Inspection and NDE	Develop guidance on NDE methods appropriate for Type IV containers	**D**
	In-service monitoring	Specify requirements and develop guidance on in-service monitoring methods	**D**

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37. ISO 19881:2018 Gaseous hydrogen – Land vehicle fuel containers

38. ANSI HGV 2-2014 Compressed hydrogen gas vehicle fuel containers

39. SAE J2579 2018 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

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42. PD ISO/TR 13086-3:2018 Gas cylinders. Guidance for design of composite cylinders. Calculation of stress ratios

43. PD ISO/TR 13086-4:2019 Gas cylinders. Guidance for design of composite cylinders. Cyclic fatigue of fibres and liners

44. ISO 11119-3:2020 Gas cylinders – Design, construction and testing of refillable composite gas cylinders and tubes. Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load sharing metallic or non-metallic liners or without liners

6 Appendix A – Detailed Approval Processes

Standardised flow chart symbols (Figure 6-1) have been used throughout the document in accordance with ISO 5807:1985 Information processing – Documentation symbols and conventions for data, program and system resources charts.

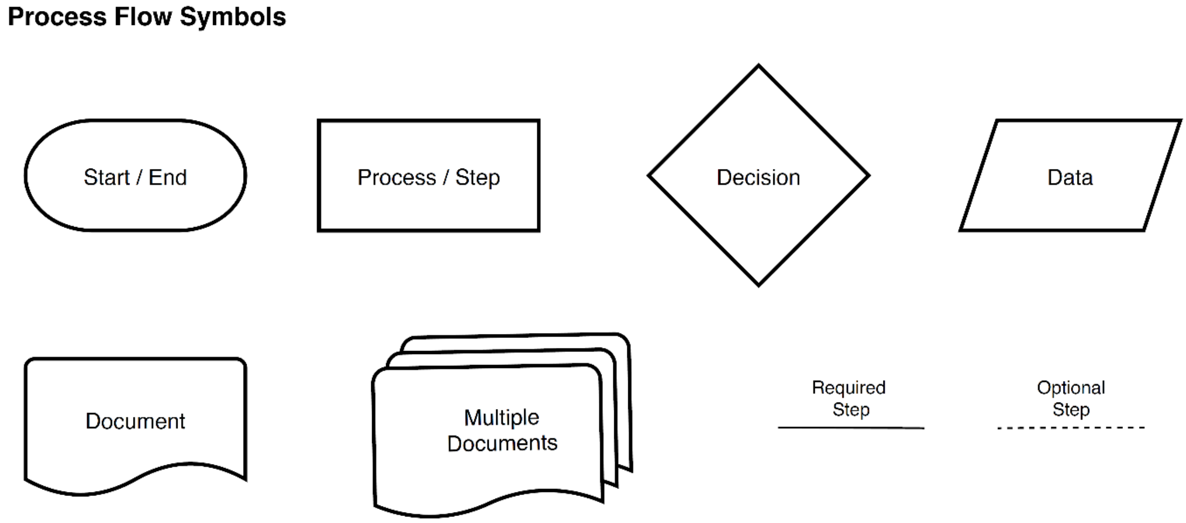
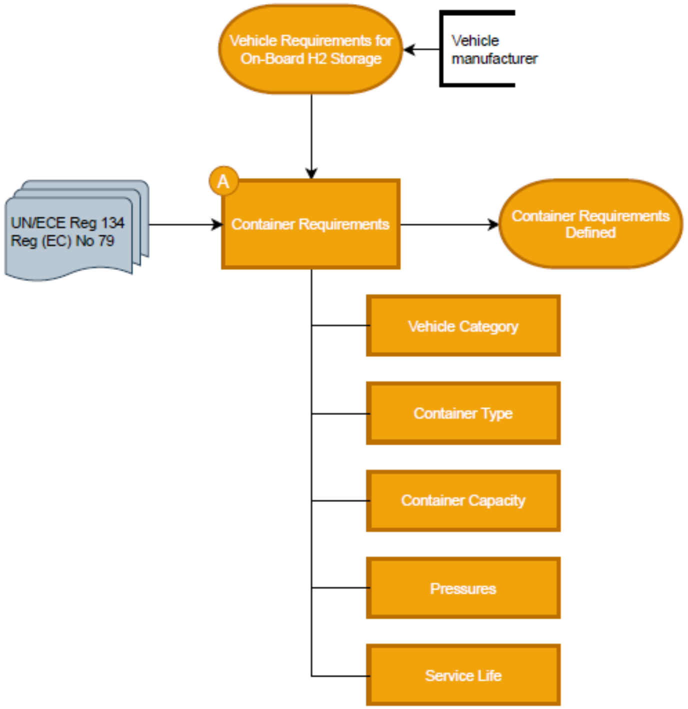


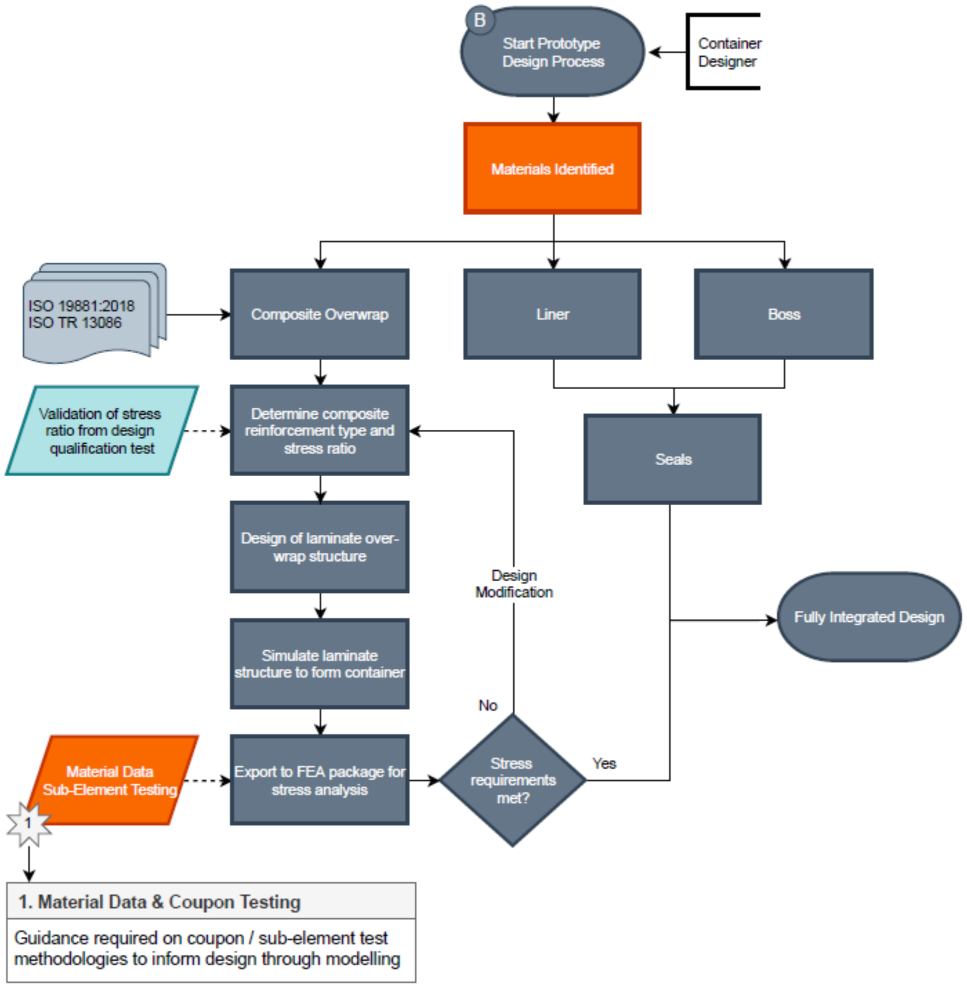
Figure 6-1 Process flow symbols used in this report accordance with ISO 5807:1985

The eight basic steps of the general approval process in Figure 4-1 are expanded below to provide an in-depth perspective of the certification process and requirements as well as identification of gaps to populate to further improve and accelerate the route to approval.

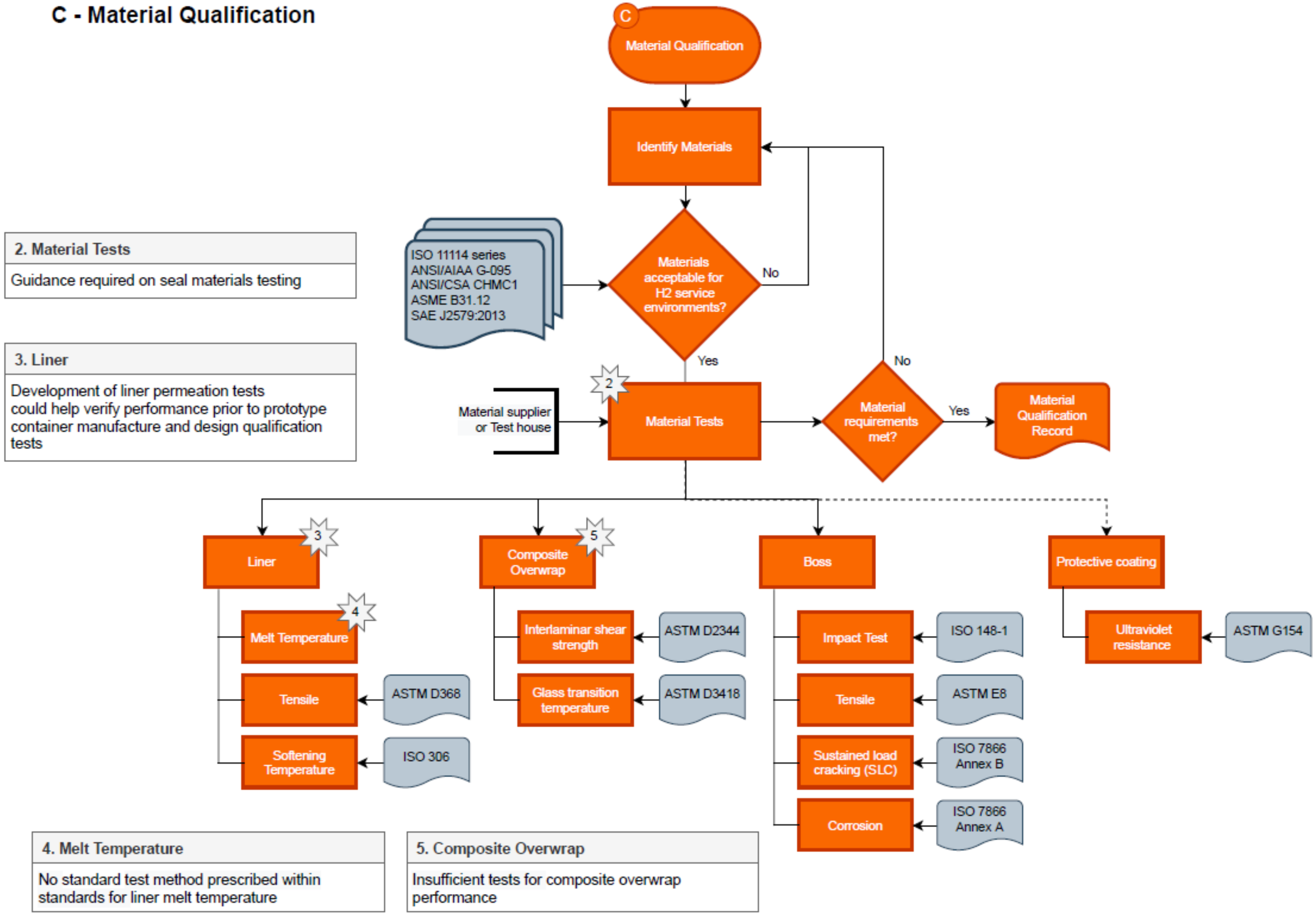
A - Container Requirements



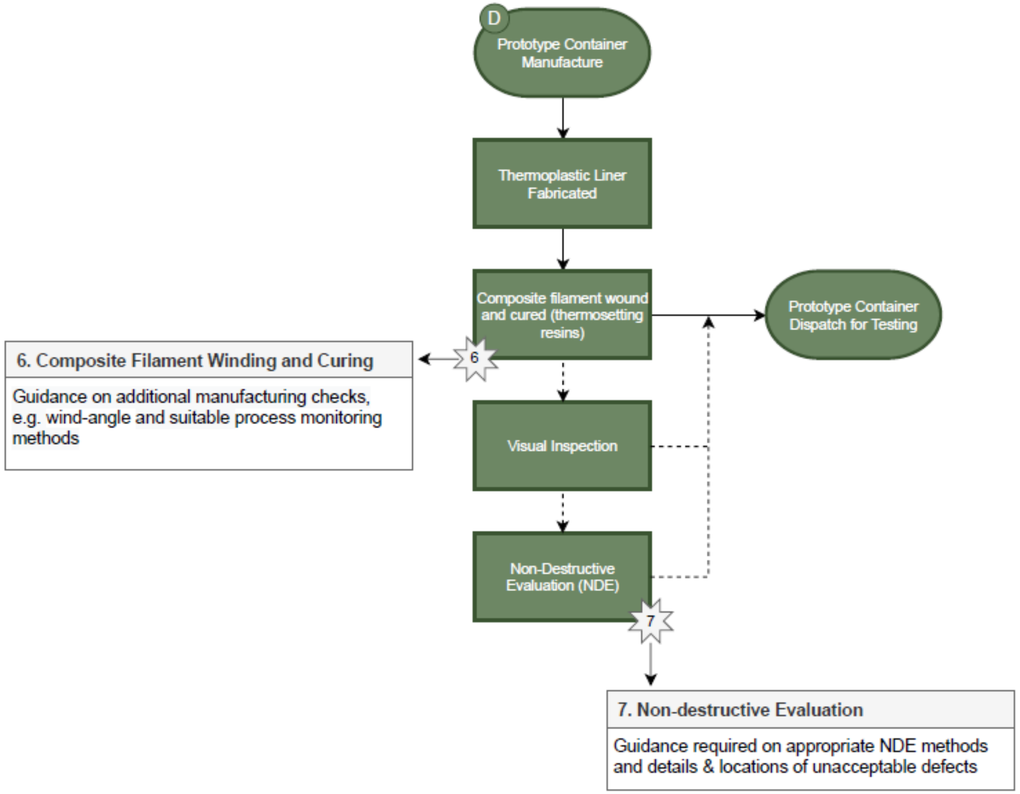
B - Prototype Design



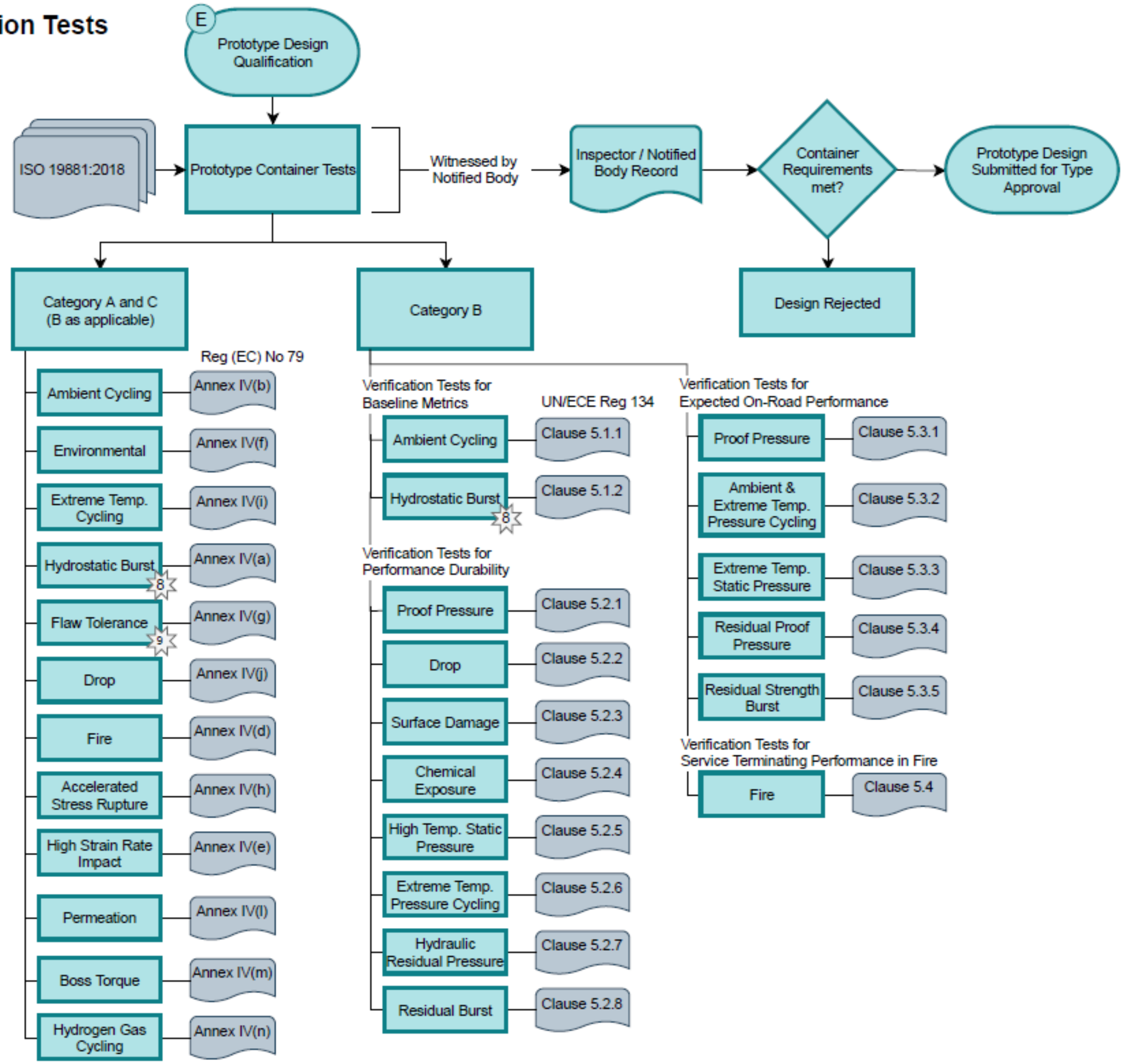
C - Material Qualification



D - Prototype Container Manufacture



E - Prototype Design Qualification Tests



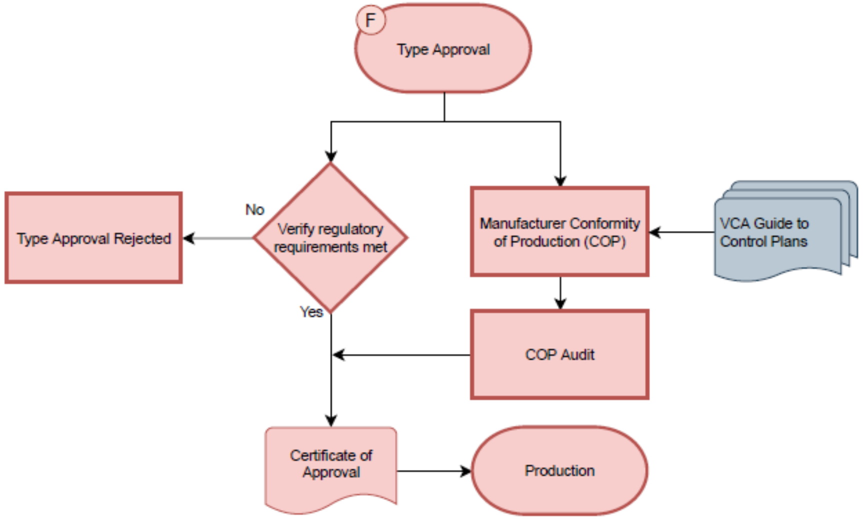
8. Hydrostatic Burst

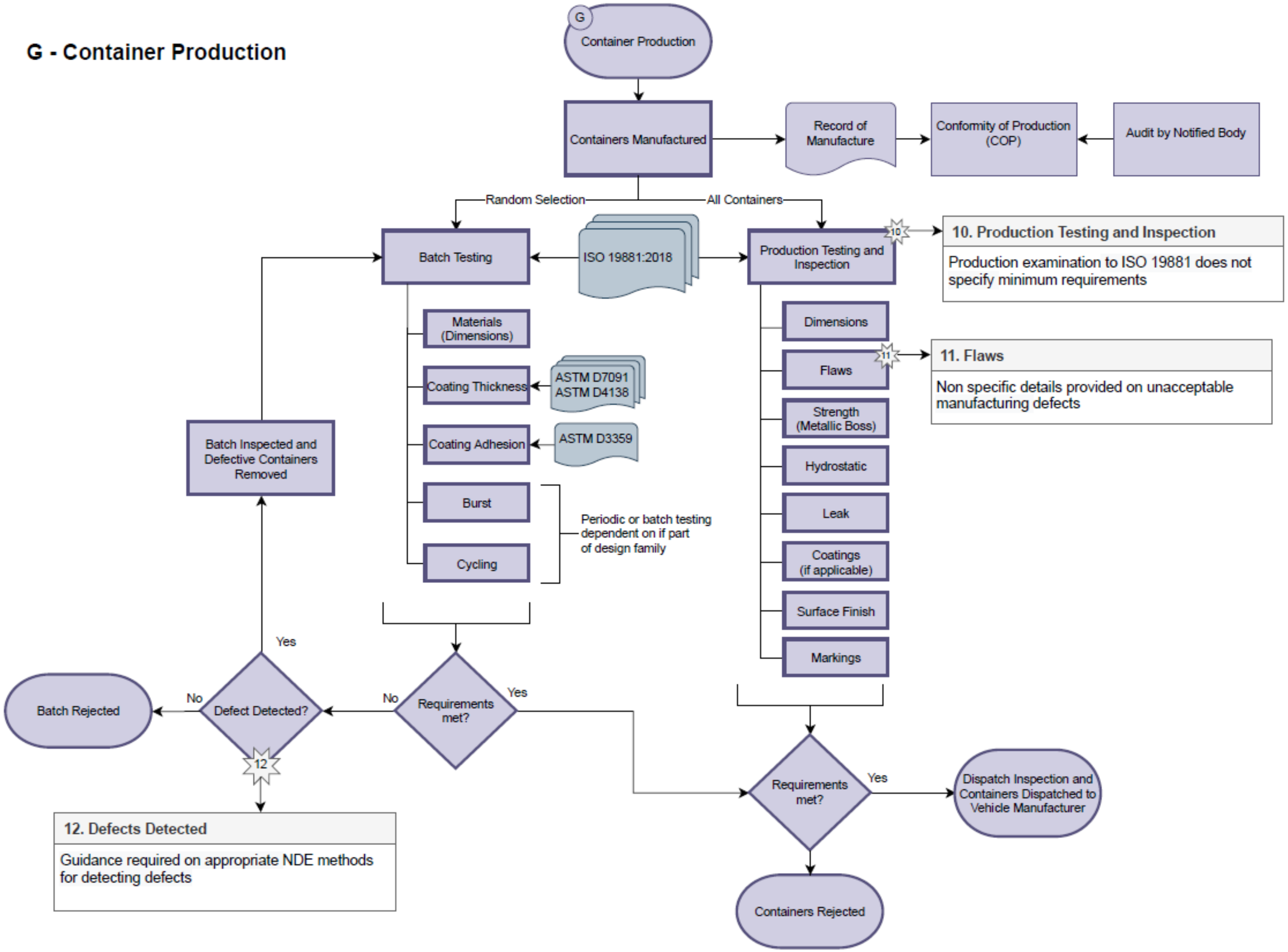
ISO 19881 hydrostatic burst test - 30 second evaluation time is deemed insufficient

9. Flaw Tolerance

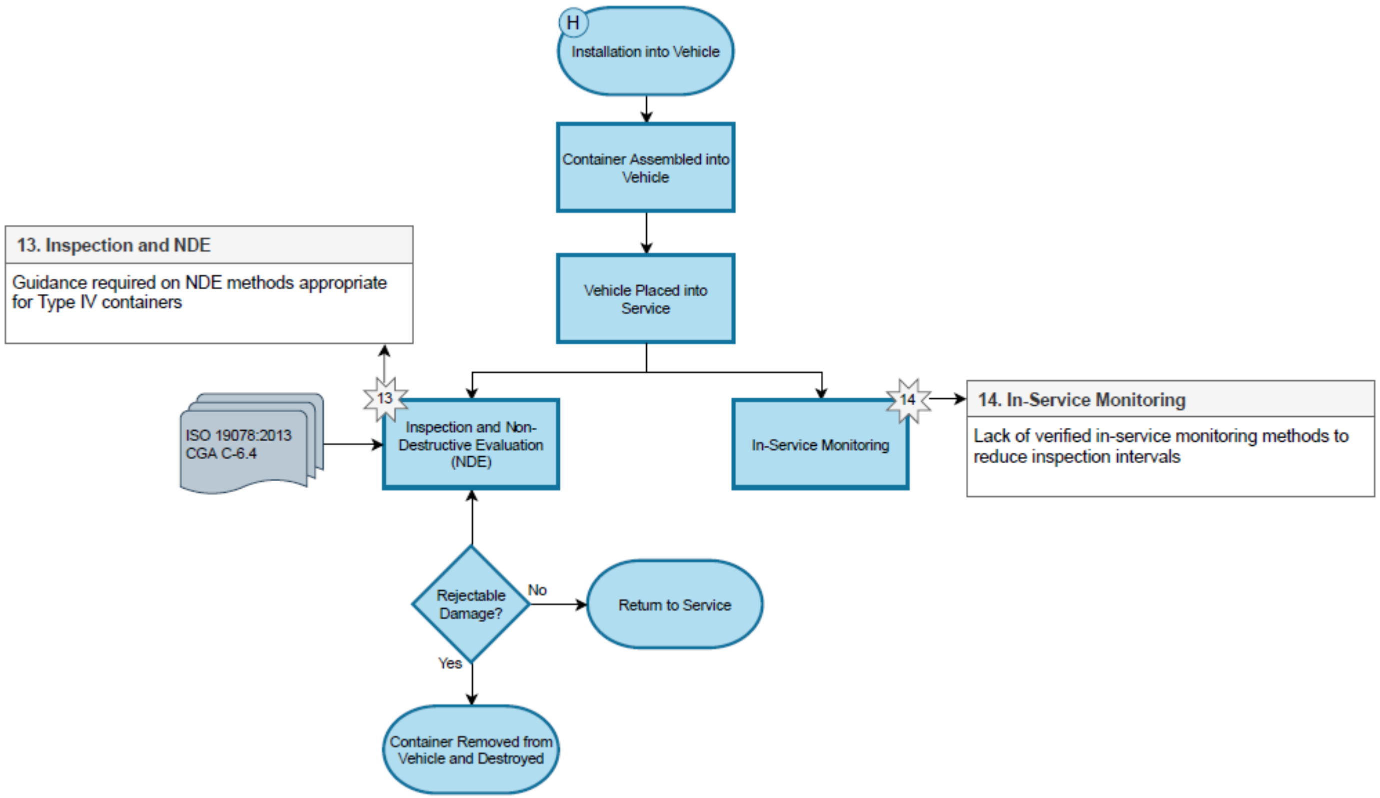
Insufficient details on geometry of flaws for flaw tolerance tests

F - Type Approval




G - Container Production
G
Container Production
Containers Manufactured
Record of Manufacture
Conformity of Production (COP)
Audit by Notified Body
Random Selection
All Containers
Batch Testing
ISO 19881:2018
Production Testing and Inspection
10
10. Production Testing and Inspection
Production examination to ISO 19881 does not specify minimum requirements
Materials (Dimensions)
Coating Thickness
ASTM D7091
ASTM D4138
Coating Adhesion
ASTM D3359
Burst
Cycling
Periodic or batch testing dependent on if part of design family
Dimensions
Flaws
11
11. Flaws
Non specific details provided on unacceptable manufacturing defects
Strength (Metallic Boss)
Hydrostatic
Leak
Coatings (if applicable)
Surface Finish
Markings
Batch Inspected and Defective Containers Removed
Yes
Batch Rejected
No
Defect Detected?
No
Requirements met?
Yes
12
12. Defects Detected
Guidance required on appropriate NDE methods for detecting defects
Requirements met?
Yes
Dispatch Inspection and Containers Dispatched to Vehicle Manufacturer
Containers Rejected

H - Installation into Vehicle



7 Appendix B – Regulations, Codes and Standards Relevant for Hydrogen Storage Containers

Regulations

European Commission. Directive 2007/46/EC establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles. Official Journal of the European Union, 2007, L 263/1

European Commission. Regulation (EU) 2018/858 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and repealing Directive 2007/46/EC. Official Journal of the European Union, 2018, L 151/1

European Commission. Regulation (EC) No 79/2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC. Official Journal of the European Union, 2009, L 35/33

Economic Commission for Europe of the United Nations (UN/ECE) Regulation No 134 of UN/ECE – Uniform provisions concerning the approval of motor vehicles and their components with regard to safety-related performance of hydrogen-fuelled vehicles (HFVC). Official Journal of the European Union, 2019, L 129/43

United Nations (UN) Global Technical Regulation No. 13. Global technical regulation on hydrogen and fuel cell vehicles. ECE/TRANS/180/Add.13, 2013

Standards

American & Canadian

ANSI HGV 2-2014
Compressed hydrogen gas vehicle fuel containers

SAE J2579 2018
Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

CSA SPE-2.1.3-2020
Best practices for defueling, decommissioning, and disposal of compressed hydrogen gas vehicle fuel containers

CSA HPIT 1-15 (R2020)
Compressed hydrogen powered industrial truck on-board fuel storage and handling components

CEN/TC 23 - Transportable gas cylinders

EN 17339:2020
Transportable gas cylinders - Fully wrapped composite cylinders and tubes for hydrogen

EN 17533:2020
Gaseous hydrogen - Cylinders and tubes for stationary storage

ISO/TC 197 - Hydrogen technologies

ISO 13985:2006
Liquid hydrogen - Land vehicle fuel tanks

ISO 19881:2018
Gaseous hydrogen - Land vehicle fuel containers

ISO 19882:2018
Gaseous hydrogen - Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers

ISO/TC 22/SC41 - Road vehicles / Specific aspects of Gaseous Fuels

ISO 12619 Series
Road vehicles - Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blend fuel system components

ISO 21266 Series
Road vehicles - Compressed gaseous hydrogen (CGH2) and hydrogen/natural gas blends fuel systems

ISO/TC 58 - Gas cylinders

ISO 11119 Series
Gas cylinders - Design, construction and testing of refillable composite gas cylinders and tubes

ISO/TR 13086 Series
Gas cylinders - Guidance for design of composite cylinders.

ISO/TS 17519:2019
Gas cylinders — Refillable permanently mounted composite tubes for transportation

ISO/ICS 23.0.20 Gas Cylinders

ISO 11114 Series
Gas cylinders - Compatibility of cylinder and valve materials with gas contents