

Non-Destructive Examination Protocols in API 650 for Welded Storage Tank Fabrication: A Comprehensive Review

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Abstract

The storage tanks play vital roles in industrial sectors, including oil and gas, manufacturing, and chemical processing by enabling safe containment of liquids and gases during key operations like production, treatment, refining, transport/distribution, and inventory control. API 650 standard is a worldwide recognized specification that covers the design and manufacturing criteria for large, welded steel storage tanks. API 650 ensures that tanks are built to withstand internal pressures and environmental variations, ensuring safety and dependability. Tanks must undergo comprehensive testing to verify structural integrity. Non-destructive examination (NDE) requirements in the fabrication of API storage tanks would likely cover a range of NDE techniques used to verify the integrity of welds, materials, and overall tank construction, referencing standards like API 650 and 653. API 650 requires reliable testing methods such as hydrostatic testing, visual inspection of welds, and various non-destructive testing (NDT) methods like radiographic, ultrasonic, magnetic particle, and liquid penetrant testing for comprehensive leak and defect detection. This paper discusses the applicability of NDE methods and techniques in compliance with API 650 for ensuring the structural integrity and safety of these tanks, especially in the context of oil and gas storage, where leaks or failures can have significant consequences. A case study on hydrotesting of heating coils also provides insights into avoiding the chances of corrosion potentiality.

Keywords: API 650, hydrostatic testing, non-destructive evaluation, storage tank integrity

INTRODUCTION

The increasing complexity, cost sensitivity, and heightened quality demands in contemporary Engineering, Procurement, and Construction (EPC) projects necessitate the adoption of advanced management frameworks, collaborative digital tools, and optimized procurement strategies to ensure successful project delivery.

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Production Functions

These vessels initially capture raw feedstocks, such as crude oil, from extraction sites to smooth out irregular supply rates and prevent production halts. In manufacturing and chemical plants, they maintain steady material availability despite variable demand.

Treatment Processes

Tanks support phase separation, allowing gravity-based removal of impurities such as water or solids from crude streams prior to further handling. They also hold wastewater processes for purification, resource recovery, and regulatory compliance.

Refining Operations

Refinery tanks buffer crude inputs, semi-processed streams, and final fuels, thereby facilitating quality blending and operational flexibility.

Transport and Distribution

Positioned at loading terminals, tanks enable efficient product dispatch via pipelines, rail, or marine vessels, with specialized designs that enhance multimodal transfers. Horizontal variants optimize petroleum handling during logistics.

Inventory Control

Equipped with precise level gauging, these tanks track stock volumes, reduce vapor losses, and ensure supply reliability across the value chain.

In this dynamic environment, the true differentiator lies in how rigorously we adhere to global standards, and API standards are at the core of this commitment. API standards provide a technical foundation for everything we engineer. API standards form the technical foundation for EPC storage tank design.

Industry standards such as API 5 L for pipeline materials and API 579 for fitness-for-service evaluations encapsulate extensive empirical knowledge, ensuring structural integrity, operational reliability, and hazard mitigation across diverse assets, such as storage tanks, rotating machinery, heat exchangers, and risk-based inspection strategies.

Standardized Applications

These codes apply rigorously to storage tanks by dictating material selection, design pressures, and corrosion allowances while extending to rotating equipment through vibration limits and alignment tolerances. For heat exchangers, specifications address tube-sheet integrity and thermal cycling, with risk-based inspection frameworks prioritizing high-consequence zones.

Continuous Process Demands

Refineries and similar facilities mandate intermediate storage to decouple sequential operations, accommodating surges in throughput or maintenance downtimes. Products remain segregated by gaseous phases in pressure vessels, liquid in atmospheric tanks, or solids in silos, to preserve stability and prevent cross-contamination.

Generally, the main requirement of the oil and petroleum industry is a tank that is required to store products safely and securely. These tanks are typically used in the petroleum industry to store crude oil, gasoline, chemicals, and other liquids at atmospheric pressure, which makes them essential for storage terminals and refineries. These tanks must follow the American Petroleum Institute (API) standards, which focus on updated policies and design requirements.

SPECIFIC APPLICATIONS

API 650-compliant welded tanks accommodate diverse fluid storage requirements across industrial sectors, leveraging their low-pressure design to ensure containment integrity under nominal operating conditions.

- *Crude oil storage:* API 650 tanks are commonly used for storing crude oil in refineries and terminals.
- *Refined petroleum products:* These vessels securely hold finished fuels such as gasoline, diesel, and aviation kerosene post-refining, thereby minimizing vapor emissions and facilitating blending operations prior to distribution.
- *Chemical containment:* The standard supports the storage of corrosive media, including acids, alkalis, and organic solvents, with material specifications addressing compatibility and lining requirements for longevity.

- *Utility water applications:* API 650 tanks serve industrial process water, firefighting reserves, and municipal supplies, and their scalable capacities meet variable demand without excessive structural demands.
- *Design pressure characteristics:* Engineered for internal pressures up to 2.5 psig, these tanks balance cost-efficiency with safety margins, rendering them versatile for non-refrigerated liquids under ambient conditions.

Advantages of API 650 Storage Tanks

API 650 provides a robust framework for constructing large-scale, aboveground welded steel storage tanks, offering broad applicability and scalability for industrial fluid containment.

- *Broad industrial versatility:* The standard extends beyond the petroleum sector to petrochemical processing, chemical manufacturing, and water management systems, accommodating varied service conditions through adaptable material and design provisions.
- *Scalable capacity range:* API 650 governs tanks from hundreds to thousands of barrels, ideal for refinery stockpiles, distribution terminals, and bulk storage, where high-volume demands necessitate durable and cost-effective structures.
- *Comprehensive design scope:* Targeting capacities above 450 liters, the code ensures structural reliability for crude oil, refined fuels, and compatible liquids under low-pressure regimes, emphasizing the weld integrity and foundation stability.
- *Versatility and wide applicability:* API 650 tanks are not limited to oil and gas applications. They are also used to store petrochemicals, chemicals, and even water in various industrial and municipal settings.
- *Large capacity:* This standard is designed for tanks with capacities exceeding 450 liters, making them ideal for large storage facilities and refineries.

The API 650 standard is an industry-accepted benchmark used in tank manufacturing and storage operations in various countries.

The expected Compound Annual Growth Rate (CAGR) for the global storage tank market, including those built into API 650 standards, is generally estimated to be approximately 6.3%–6.7% over the next few years, with most forecasts spanning from 2025 to 2032 [1]. This growth is driven by factors such as infrastructure investments, expansion of the petrochemical industry, and increasing demand for oil and gas storage.

Scope of API 650 Standard

The API 650 standard was first published in December 1961 [2]. API 650 tanks are versatile, widely used for large capacity, aboveground welded steel storage, and are suitable for various liquids and industries beyond oil and gas. API 650 establishes minimum requirements for designing, fabricating, erecting, and inspecting large, vertical, cylindrical, aboveground, and welded steel storage tanks operating near atmospheric pressure.

Core Design Parameters

The standard targets non-refrigerated tanks with uniformly supported flat bottoms, internal pressures not exceeding the roof plate weight (up to 17.2 kPa with reinforcements), and maximum operating temperatures of 93°C [3]. Capacities start above 450 liters, supporting liquids ranging from crude oil and refined fuels to chemicals and process water.

API 650 and Its Comparison with Other Codes/Standards

API 650 represents a cornerstone standard for vertical, cylindrical, and aboveground welded steel storage tanks, with distinct attributes compared with complementary codes such as API 620 and API 12F.

Comparison with API 12F

API 650 accommodates expansive tank sizes and broad applications across oil, chemical, and water storage, whereas API 12F targets compact, shop-fabricated units optimized for field lease operations in upstream oil and gas, prioritizing rapid assembly over scalability [4].

Comparison with API 620

Although API 650 governs atmospheric tanks (up to 17.2 kPa) suited for high-temperature fluids up to 93°C, API 620 addresses low-pressure vessels (up to 103 kPa) with rigorous reinforcements for vapors, cryogenics, or Liquefied Natural Gas (LNG), demanding advanced design analyses for high-temperature requirements [5–7].

Selection Criteria

Project demands, encompassing size, operating pressure, temperature profile, and service fluid, dictate standard adoption, ensuring alignment with safety, cost, and performance imperatives across the refinery, petrochemical, and biofuel contexts.

API 650 establishes the engineering, material, design, and construction criteria for the fabrication of new welded steel storage tanks, ensuring structural integrity and regulatory compliance throughout the tank lifecycle. API 653 provides comprehensive guidelines for the inspection, repair, alteration, and reconstruction of existing aboveground storage tanks, building directly on API 650 design principles [8]. This standard ensures that tanks remain fit-for-service through systematic evaluations of shell thickness, bottom integrity, roof conditions, and foundations while mandating hydrotesting or alternative proof methods post-modifications. API 653 enables the life extension of aging assets in refineries and terminals by specifying fitness-for-service assessments, rerating procedures, and hot-tap protocols, thereby minimizing downtime and enhancing safety compliance. API 653 provides essential protocols for inspecting, repairing, altering, and reconstructing existing aboveground storage tanks previously built according to standards such as API 650.

API Tanks differ from ASME tanks in terms of their internal pressure. The ASME tank had an internal pressure of more than 103 kPa.

DESIGN AND ENGINEERING REQUIREMENTS

API 650 standards are primarily designed for large, field-erected, and aboveground storage tanks. Although they may not apply to all tank types, they are crucial for industries where safety and environmental protection are paramount. API 650 standards are vital for ensuring the safe design, construction, and maintenance of aboveground storage tanks, particularly in industries dealing with hazardous substances. The correct selection, design, and configuration of atmospheric tanks according to API 650 are key to ensuring the safety and efficiency of liquid storage [9]. It is of utmost importance that tanks are designed and built considering all operational and environmental aspects for a defined lifetime of usually 30 years [10].

Key API 650 Guidelines

API 650 offers detailed standards for designing and constructing Above Ground Storage Tanks. Essential provisions include:

- *Material selection and fabrication:* Specify steel grades, welding procedures, and quality controls to ensure durability and leak prevention.
- *Structural integrity:* Shell thickness, bottom reinforcement, and roof design are calculated to resist hydrostatic loads, wind, seismic forces, and settlement.
- *Foundations and anchorage:* Mandate stable base preparation, including soil testing and pile systems, to prevent uneven settling or uplift.

- *Appurtenances and accessories*: Detailed requirements for vents, ladders, gauging devices, and emergency venting to manage pressure safely.
- *Testing and inspection*: Outline hydrostatic testing, non-destructive examination (NDE), and compliance certification protocols.

These standards minimize risks in petroleum, chemical, and water storage applications.

Design and Fabrication

Tanks are designed to meet specific requirements, including the capacity, pressure, and temperature limits [11]. The primary stresses in a cylindrical storage tank are the hoop (circumferential) and longitudinal (axial) stresses. Hoop stress is the stress exerted in the circumferential direction of the cylindrical wall. This stress acts perpendicular to the axis of the cylinder and is often the most significant stress in cylindrical storage tanks [12].

Aboveground storage tanks (ASTs) built into API 650 operate under nominal atmospheric conditions, lacking capacity for substantial internal pressure or vacuum, and thus depend on passive ventilation alongside external venting mechanisms to accommodate volumetric shifts from filling, draining, or thermal effects, as shown in Figure 1.

Principal Structural Elements

ASTs comprise flat bottoms, annular shell courses, and supported roofs augmented by process nozzles, gauging ports, ladders, and appurtenances, such as floating roofs or suction lines tailored to service fluids.

Design Stress Regimes

API 650 mandates the analysis of hoop (circumferential) and radial (longitudinal) stresses in cylindrical shells, with hoop tension dominating owing to internal hydrostatic loading and requiring precise thickness calculations.

Design Metal Temperature

Design metal temperature (DMT) defines the minimum anticipated shell temperature, guiding carbon steel grades and impact testing to avert brittle failure under cooling scenarios.

API 650 mandates the selection of materials that retain ductility and toughness at the DMT to prevent brittle fractures during service. API 650 requires materials to have a suitable notch toughness at the DMT. The DMT ensures that the tank material maintains ductility and toughness under the coldest operating conditions, thereby enhancing safety. Thermal expansion affects the tank dimensions owing to the temperature changes. API 650 requires designers to consider the expansion in material selection, joint design, and structural allowances.

Provisions include flexible connections, expansion joints, and proper spacing to prevent stress or distortions that could compromise the tank's integrity. Temperature is an important factor in pressure testing and in API 650 storage tanks. API 650 storage tanks operate within defined temperature ranges to ensure material performance and structural integrity. According to the specifications, depending on the materials used in construction, these tanks may withstand temperatures ranging from -40°C to 260°C . This wide temperature range allows for safe storage of a variety of products, including cryogenic liquids and high-temperature chemicals. It is important to note that exceeding these temperature limits during testing or operation can jeopardize the structural integrity of the tank, resulting in fractures, deformities, or other issues.

Tank Types

Storage tanks are categorized according to their stored fluid characteristics, operational pressure ratings, and roof configurations to optimize safety and functionality. According to API Standards 650

and 620, storage tanks are classified based on the design pressure and intended service. The two most common categories are atmospheric and pressurized tanks.

Fluid-Based Classification

Tanks segregate by media properties, such as petroleum products, chemicals, water, dictating material compatibility, linings, and appurtenances, such as floating roofs for volatile organics.

Pressure Rating Categories

Designations span fixed roof atmospheric units (API 650), low-pressure vessels (API 620), and pressurized spheres, aligning the containment with vapor pressure thresholds.

Roof Configuration Types

Variants include cone-roofs, dome-roofs, or internal/external floating roofs, which are selected to curb emissions, accommodate thermal expansion, and suit inventory management needs.

Atmospheric Tanks

Atmospheric tanks operate at or near ambient pressure, with API 650 Annex F permitting designs of up to an internal pressure 18 kPa.

Design Configurations

These include fixed roof variants for controlled environments, floating roof systems to minimize vapor space, and open-top configurations for nonvolatile, nonweather-sensitive fluids.

Open-Top Applications

Lacking overhead enclosures, open-top tanks suit solids or low-hazard liquids exempt from explosion safeguards or precipitation shielding, prioritizing ventilation and access simplicity. These tanks are designed to operate at pressures close to the atmospheric pressure. Fixed roof tanks have a rigid, non-moving roof designed to store liquids with low volatility, such as water or chemicals. Fixed roof tanks were used for nonvolatile liquids. Floating roof tanks are used for volatile liquids, such as crude oil, and pressure tanks for gases or liquids under high pressure.

Other types include vertical and horizontal designs, which are distinguished by their orientation, and location-based classifications, such as aboveground and underground tanks. ASTs are used in almost all industrial applications, where storage of large liquid substances is a part of the process. The most important application is the storage of hydrocarbon and petrochemical products in welded, vertical, and cylindrical ASTs. Figure 2 shows the classification/type of the storage tanks. API 650 tanks are typically vertical, cylindrical, and flat-bottomed with options for conical or domed roofs.

Pressure Tanks

Pressure Tanks Engineered to store substances under high pressure and are often used for gases or highly volatile liquids. Cryogenic storage tanks maintain ultra-low temperatures essential for liquefied gases, such as LNG, LIN, LAR, and Liquid Oxygen (LOX), preventing phase transitions and boil-off losses.

Specialized Design Features

These vessels employ perlite insulation, double-wall vacuum jacketing, and materials, such as 9% nickel steel, to withstand thermal contraction and extreme differentials down to -196°C.

Operational Scope

Governed by standards beyond API 650, such as API 620 supplements, cryogenic tanks support LNG terminals, industrial gas plants, and aerospace fueling, and prioritize leak tightness and seismic resilience. Various types of atmospheric and pressurized storage tanks are shown in Figure 3.

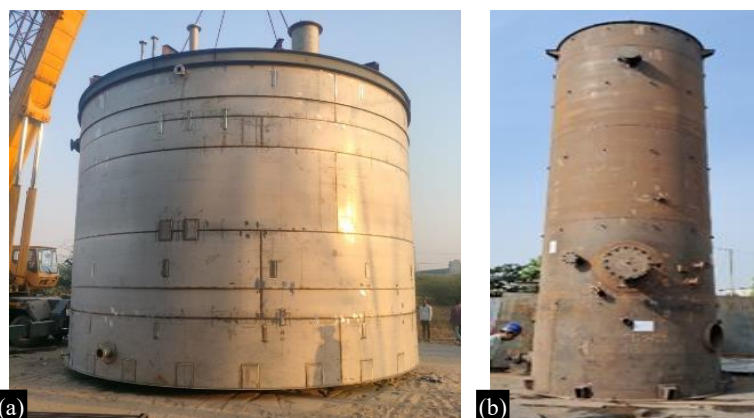


Figure 1. (a) and (b) Stainless steel and carbon steel aboveground storage tanks.

Photo courtesy: (a) Shop inspection at Sparkon Engineers, Galenda, Gujarat, India, and (b) TEMA India Private Limited, Panoli, Gujarat, India.

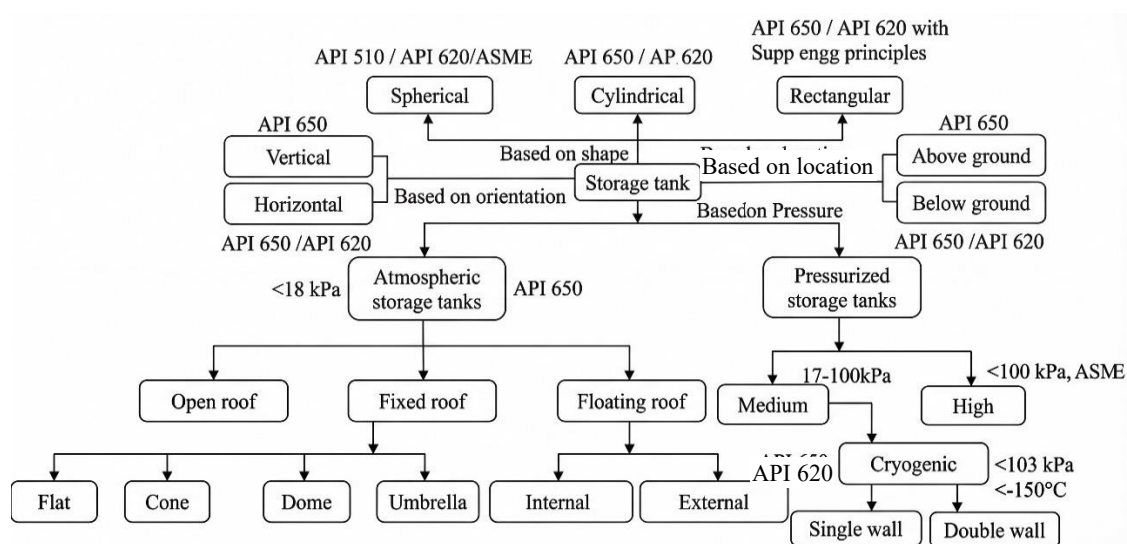


Figure 2. Type of storage tanks.

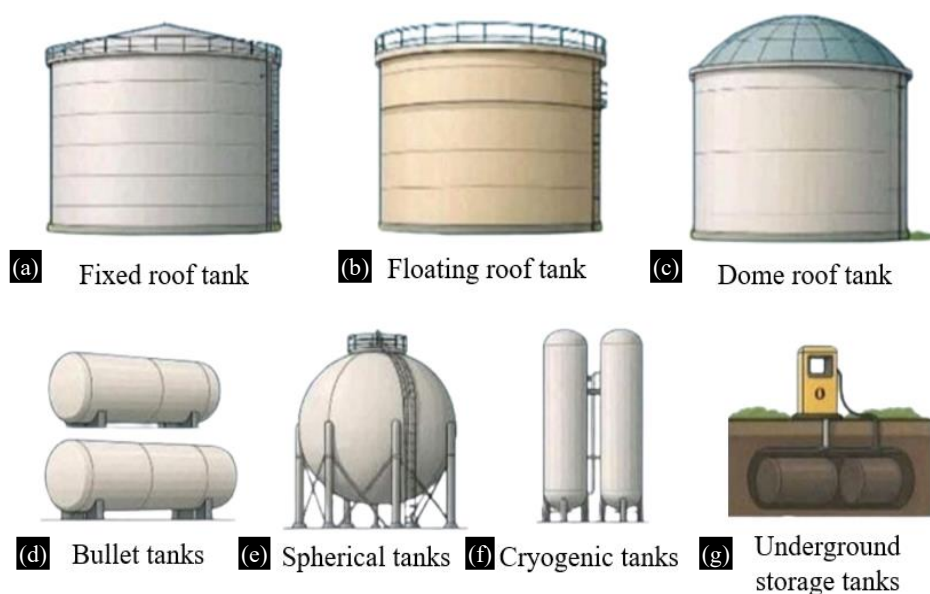


Figure 3. (a) to (g) Understanding storage tank types employed in the oil and gas industry.

Material Selection

Material selection is crucial for ensuring structural integrity, durability, and compliance with environmental conditions. Factors influencing material choice include the chemical properties of the stored product, operating temperature, DMT, corrosion allowances, and tank location. Proper material selection minimizes risks such as brittle fracture and corrosion, ensuring long-term performance. Fabrication aids for storage tanks must preserve structural integrity without inducing corrosion, embrittlement, or mechanical degradation. “(API 650, Section 6.1.1.3, 2025)” [2].

API 650 does not prescribe a single material for specific liquids, such as water or diesel, but requires that materials be selected from those approved in the standard.

The material selection for the tank shell in API 650 was determined by considering the material strength, toughness, and corrosion resistance. Material selection depends on factors such as stored fluid properties, temperature, pressure, corrosion resistance, and regulatory compliance [13, 14]. The storage tank design integrates fluid characteristics, ambient exposures, pressure profiles, and regulatory codes to avert leaks, spills, fires, or fire hazards [15].

Material Selection Criteria

Erection materials conform to the design norms, fabrication protocols, stringent testing regimes, and certification markings, predominantly carbon steel for economy or stainless steel for enhanced corrosion barriers [16].

Fabrication Safeguards

Carbon steel is suitable for non-aggressive petroleum and water services because of its cost advantages, whereas stainless steel grades protect against acids, salts, or oxidizers in chemical duties, with aluminum reserved for select low-stress applications.

While carbon steel is commonly used in API 650 tanks, stainless steel offers advantages in terms of corrosion resistance and can be a suitable choice when dealing with corrosive substances or when long-term durability is a primary concern. Stainless steel is the preferred material in applications where the stored material is corrosive or where prolonged service life is required.

These standards mandate the use of carbon or low-alloy steel that conforms to specific mechanical properties to ensure tank integrity. According to this standard, the shell plate should be constructed using carbon or low-alloy steel, and the maximum carbon content must not exceed 0.21%. The carbon content was limited to 0.23% max. The toughness and weldability of a material can be affected by carbon content, and an increase in the carbon content can lead to a higher risk of cracking during welding. Several factors, such as corrosion resistance, operating temperature, and cost, determine the material choice. Stainless steel tanks often incur lower lifecycle costs than their carbon steel counterparts owing to reduced maintenance demands and superior resistance to thermal cracking.

Corrosion and Durability Advantages

Stainless variants exhibit markedly slower degradation rates in aggressive environments, minimize interventions, and preserve bottom integrity over extended service intervals.

Carbon Steel Specifications

For benign services, such as crude oil, fuels, and process water, industry practice favors ASTM A36, A283 Grades C/D, A285 Grade C, and A516 Grades 55/60/65/70, balancing weldability, strength, and affordability.

When higher strength and improved mechanical properties are required, typically for thicker tank shells or components subjected to higher stress or severe service conditions, the specifications and grades/classes generally employed for low-alloy steels are ASTM A537 Class 1 A633 Gr. C/E.

Highly corrosive products, such as acids and ammonia, or when the product should not be contaminated by any corrosion (potable water, high-oxygen products, special jet fuels, etc.), the specifications and grades/classes generally employed for Stainless Steels are ASTM A240 Type 304/304L, Type 316/316L.

When superior corrosion resistance is required, especially in environments containing chlorides, aggressive chemicals, or seawater, the specifications and grades/classes generally employed for duplex stainless steel are ASTM A240 Duplex 2205 (UNS S32205). Duplex 2205 stainless-steel combines elevated mechanical strength with robust resistance to pitting, stress corrosion cracking, and crevice corrosion, making it ideal for tanks.

Performance Attributes

This alloy's balanced microstructure, approximately equal austenite and ferrite phases, delivers yield strengths exceeding 450 MPa alongside pitting resistance equivalent numbers (PREN) above 35, outperforming standard austenitic in chloride-laden services.

Application Suitability

In storage tanks handling brackish process water or mildly acidic hydrocarbons, duplex 2205 minimizes wall thinning and crack propagation risks, extending the intervals between inspections and recoating.

When corrosion resistance, lightweight design, and non-magnetic properties are required, the specifications and grades/classes generally employed for aluminum alloys are ASTM B209 5052/5083/6061.

All pressure-retaining parts (including gaskets, studs, and nuts) were certified under an inspection certificate EN10204 Type 3.1. All non-pressure parts were certified to the inspection certificate EN10204 Type 2.2.

Minimum Required Shell Thickness

The shell thickness calculations per API 650 ensured structural adequacy against hydrostatic and internal pressure loads while respecting the material yield limits.

CALCULATION METHODOLOGY

Formulae integrate the liquid head pressure, design girth stress (typically one-third of the specified minimum yield), corrosion allowances, and joint efficiencies to establish the minimum thickness for each shell course.

DESIGN IMPLICATIONS

This approach yields tapered shells that are thicker at base elevations to optimize material usage, with mandatory minimums preventing localized instability under wind, seismic, or vacuum conditions.

The formula accounts for factors such as design-specific gravity, tank diameter, joint efficiency, and corrosion allowance. Ensuring adequate thickness is essential for structural integrity under operational loads. The shell thickness was calculated based on internal pressure, material strength, joint efficiency, and corrosion allowance using formulae specified in the API 650 standards. Shell thickness requirements mandate the selection of a greater value between the design thickness (incorporating corrosion allowance) and hydrostatic test thickness to maintain integrity under operational and proof conditions. "(API 650, Section 5.6.1.1, 2025)" [2]. Shell courses were arranged with varying thicknesses, with thicker plates at the bottom to withstand higher hydrostatic pressure, ensuring both structural efficiency and cost optimization. Austenitic stainless-steel storage tanks require bottom plates to maintain a minimum corroded thickness of 6 mm, safeguarding against perforation and leakage under prolonged service. "(API 650, Section S.3.1.2, 2025)" [2].

Corrosion Protection Role

This threshold accommodates uniform and localized thinning from service fluids, ensuring hydraulic isolation and structural support for shell loads throughout the design life of the tank.

Compliance Verification

Thickness surveys via ultrasonic testing during API 653 inspections confirm adherence, triggering lap patch repairs or bottom replacement when averages fall below the mandated limits.

The mill tolerance should be on the positive side of the plate material. A mill under tolerance is not acceptable.

Joint Efficiency

Joint efficiency refers to the strength of the welded joints relative to the base metal strength. In API 650, joint efficiency factors are used in shell thickness calculations to account for potential weaknesses in the welds, as shown in Table 1. A lower joint efficiency requires thicker shell plates to compensate, ensuring that the tank can withstand internal pressures without failure [17]. For Austenitic Stainless-Steel tanks, the following is followed regarding the joint efficiencies:

Nozzle

Nozzle flange dimensions up to NPS 24 were as per ASME B16.5 [18]. The projection of the nozzles was measured from the intersection of the nozzle axis at the outer surface of the shell roof and the flange face. Nozzle reinforcement strengthens the tank shell around the openings to compensate for the removed material and stress concentrations. API 650 provides calculation methods to determine the required reinforcement area based on nozzle size, shell thickness, and material properties. Proper reinforcement prevents failures at the nozzles owing to internal and external pressures. The RF pad was provided with min. One 6 mm diameter vent hole and for a nozzle size greater than 400 NB shall have min. 2 nos., and greater than 900 NB have min. 4 nos. vent holes. The holes were plugged with grease after testing. Nozzles 50 NB and below were stiffened with two nos. of a 40w × 6 mm stiffener at 90° apart. Companion flanges are provided along with bolts, nuts, and gaskets for all nozzles. Nozzles equipped with blind flanges require gaskets, studs, and nuts to ensure leak-tight sealing under the operational and test conditions.

Bolting Specifications

All inch-series bolting and threading conform to ASME B1.1 [19], with UNC-2A/2 B threads for sizes up to 1 inch and eight threads per inch for larger diameters, achieving Class 2A external and Class 2 B internal fits.

Flange Alignment Requirements

Bolt holes must straddle vessel centerlines precisely to promote uniform load distribution, gasket compression, and resistance to pressure-induced distortions during service.

Corrosion Protection

The corrosion allowance incorporates additional metal thickness into the tank components to offset gradual material degradation from corrosive service environments.

Purpose and Mechanism

This provision sustains minimum structural thickness throughout the design life, accommodating uniform thinning from internal fluids or external soils without compromising pressure containment or leak prevention.

Implementation Strategy

API 650 calculates tailor allowances, typically 1–6 mm, based on historical corrosion rates, fluid pH, and exposure duration, verified through periodic ultrasonic profiling during API 653 inspections.

Determined based on the corrosiveness of the stored products, environmental conditions, and expected service life, it ensures that the tank remains structurally sound despite corrosion. The corrosion allowance compensates for material loss due to corrosion over the tank's lifecycle, ensuring structural integrity and safe operation, even after prolonged exposure to corrosive environments.

API 650 recognizes the necessity of corrosion mitigation for tank bottoms interfacing with soil, although the detailed cathodic protection criteria reside in the National Association of Corrosion Engineers (NACE) standards.

Cathodic Protection Mechanism

These systems render the tank structure cathodic within an electrochemical cell, countering anodic dissolution through sacrificial anodes or impressed currents, thereby arresting under-bottom pitting and extending the service intervals.

Integration with Tank Integrity

Complementing API 653 inspections, cathodic protection surveys monitor polarization potentials, ensure uniform protection across pad foundations, and minimize excavation requirements for bottom plate renewals.

Roof Type

The roof type selection for storage tanks aligns with operational demands, including fixed roofs for routine containment, external floating roofs for volatile fluids, and domed roofs for elevated pressures or expansive diameters, as shown in Figure 4.

Fixed Cone Roof Prevalence

Cone-shaped roofs, prevalent in fixed configurations for carbon and stainless-steel tanks, facilitate efficient drainage, structural rigidity, and economical fabrication across diverse capacities.

Design Rationale

This geometry optimizes snow shedding, wind resistance, and appurtenance mounting, while complying with API 650 provisions for low-pressure services, as illustrated in typical sectional profiles.

WORKMANSHIP

API 650 mandates superior workmanship throughout tank fabrication and erection to guarantee structural reliability and service performance.

Material Conditioning Requirements

Carbon steel plates must arrive in the as-rolled condition with a minimum nominal width of 1800 mm for butt-welded shell courses, ensuring edge squareness, while forgings and fittings undergo normalization with fine-grain practices.

Inspection and Rejection Protocols

The manufacturer's inspector conducts rigorous scrutiny, rejecting any substandard materials or flawed craftsmanship, with purchasers empowered to demand prompt replacements and exclude non-conforming elements from contract incorporation.

WELDING

Preparation for Welding

Parts to be cut and parts to be bent shall be subjected to visual inspection, and there are no harmful defects, such as groove face defects, notch defects, surface defects, etc. The roof type selection for storage tanks aligns with operational demands, including fixed roofs for routine containment, external floating roofs for volatile fluids, and domed roofs for elevated pressures or expansive diameters.

Welding of API Storage Tanks

API 650 Section 9 mandates that all welding on ASTs strictly adhere to manufacturer-qualified welding procedure specifications (WPS) and corresponding procedure qualification records (PQR).

Qualification Imperatives

WPS documents predefined parameters, such as electrode types, preheat levels, and interpass temperatures, whereas PQRs validate these through destructive testing, ensuring that weldments withstand hoop stresses and corrosion-fatigue cycles.

Compliance Assurance

This framework guarantees radiographic quality levels, welder certifications, and repair protocols, minimizing lamellar tearing or hydrogen cracking risks during shell erection and nozzle attachment.

All welding was performed according to the approved WPS. API 650 specifies the welding procedures, welder qualifications, and weld inspection methods to ensure high-quality welds. The requirements include prequalified welding procedures, welder certification, and adherence to acceptable welding processes. These standards prevent defects that could compromise tank integrity, such as cracks or leaks, thereby ensuring safety and reliability. Welding must follow prescribed procedures using qualified welders and materials. Welding operators were tested and certified in accordance with the tank builder's welding procedures.

Shield metal arc welding (SMAW), also known as stick (arc) welding, is the leading welding process and is still very common today for the construction of ground storage tanks. API 650 Section 9 mandates strict adherence to manufacturer-developed WPS and validates PQR for all tank welding operations.

SMAW Process Suitability

SMAW excels in field erection environments, requiring low-hydrogen electrodes for annular plates, shell-to-bottom joints, and thicker Group I–III steels (>12.5 mm), or all thicknesses in higher strength Groups IV–VI.

Consumable and Joint Requirements

Electrodes match the material tensile strengths, E60/E70 series per AWS A5.1 for <550 MPa, E80XX-CX per AWS A5.5, 550–585 MPa, with full-penetration butt welds cleaned layer-by-layer, back-chipped to sound metal, and root runs via Gas Tungsten Arc Welding (GTAW), where double-sided access proves impractical.

Tank shell/head/roof plate weld seams should be arranged such that they do not intersect the nozzles and gusset plates. Vertical joints should preferably be offset by at least 1000 mm.

All welding faces and adjoining surfaces for a distance of at least 50 mm from the edge of the welding groove or 12 mm from the toe of the fillet in the case of fillet-welded or socket-welded joints. API 650 enforces precise joint positioning, weld sequencing, and attachment protocols to minimize residual stresses, distortions, and stress concentrations during tank erection.

Joint and Clearance Specifications

Lap joints maintain close plate contact, butt welds form all bottom seams, and vertical shell joints offset annular welds by at least 300 mm while avoiding nozzle or pad intersections, with shell-to-bottom connections requiring a minimum of two-pass welds.

Attachment and Sequencing Controls

Curb angles and stiffeners stagger from vertical seams, roof plates secure via continuous fillet welds to top angles, and platforms utilize independent supports; fabrication drawings delineate distortion-minimizing sequences, completing repairs, and NDE prior to pad applications.

Hydrotest Welding Constraints

Structural shell attachments 1 m above the waterline and roof fittings permit welding during hydrostatic testing, whereas nonstructural elements require post-test completion to preserve proof integrity.

INSPECTION AND TESTING

The inspection and testing regimes for API 650 storage tanks verify weld integrity, material soundness, and overall structural compliance prior to commissioning.

Primary Inspection Categories

NDE delivers immediate flaw detection, risk-based inspection (RBI) targets high-consequence zones through probabilistic modeling, and time-based protocols enforce statutory intervals, collectively averting leaks and failures.

Examination Prerequisites

Final welds undergo slag removal and decontamination from oils, paints, or residues to facilitate unambiguous radiographic, ultrasonic, or magnetic particle interpretation across the bottom, shell, roof, and attachment.

Welding processes and inspection protocols underpin the structural reliability and operational safety of the newly constructed ASTs.

Inspection Methodologies

NDE provides immediate defect characterization, RBI allocates resources to elevated threat potentials via failure probability analyses, and time-based schedules fulfill jurisdictional mandates, jointly curtailing rupture risks and unplanned outages.

Pre-Examination Protocols

Weld surfaces require complete slag, grease, paint, and contaminant removal to enable unequivocal radiographic, ultrasonic, or dye penetrant readings on the bottoms, shells, roofs, and seam intersections, as shown in Table 2.

API 650 mandates radiographic or ultrasonic evaluation of specified welds per Sections 8.1 and 8.3, supplemented by mandatory visual examination to confirm the surface quality.

Bottom Weld Inspection Protocols

Post-welding, tank bottoms undergo visual scrutiny for leaks, defects, and irregularities, including sumps, dents, arc strikes, and lap junctions, with verified slopes.

Acceptance and Supplemental Testing

Section 8.5 delineates the visual criteria, while Section 7.3.3 authorizes the vacuum box, tracer gas, or liquid penetrant methods on all bottom seams to detect subsurface discontinuities prior to hydrostatic proof.

Table 1. Joint efficiency values and corresponding radiographic requirements as per API 650.

Joint efficiency	Radiograph requirements
1.0	Radiograph per 8.1.2
0.85	Radiograph per A.5.3
0.70	No radiography required

Table 2. Dimensional tolerances.

Item	Tolerances	Reference Section										
Plumbness	The maximum out-of-plumbness of the top of the shell relative to the bottom of the shell shall not exceed 1/200 of the total tank height. The out-of-plumbness in one shell course shall not exceed the permissible variations for flatness and waviness as specified in ASTM A6M/A6, ASTM A20M/A20, or ASTM A480M/A480, whichever is applicable.	See 7.5.2										
Roundness	Radii measured at 0.3 m (1 ft) above the bottom corner shall not exceed the following tolerances: <table><tr><th>Tank Diameter m (ft)</th><th>Radius Tolerance mm (in.)</th></tr><tr><td>< 12 (40)</td><td>± 13 (1/2)</td></tr><tr><td>From 12 (40) to < 45 (150)</td><td>± 19 (3/4)</td></tr><tr><td>From 45 (150) to < 75 (250)</td><td>± 25 (1)</td></tr><tr><td>≥ 75 (250)</td><td>± 32 (1 1/4)</td></tr></table>	Tank Diameter m (ft)	Radius Tolerance mm (in.)	< 12 (40)	± 13 (1/2)	From 12 (40) to < 45 (150)	± 19 (3/4)	From 45 (150) to < 75 (250)	± 25 (1)	≥ 75 (250)	± 32 (1 1/4)	See 7.5.3
Tank Diameter m (ft)	Radius Tolerance mm (in.)											
< 12 (40)	± 13 (1/2)											
From 12 (40) to < 45 (150)	± 19 (3/4)											
From 45 (150) to < 75 (250)	± 25 (1)											
≥ 75 (250)	± 32 (1 1/4)											
Peaking	Deviations at vertical weld joints shall not exceed 13 mm. (By using a sweep board 90 cm long with the same radius as the tank).	See 7.5.4 (a)										
Banding	Deviations at horizontal weld joints shall not exceed 13 mm. (By using a 90 cm straight edge vertical sweep board).	See 7.5.4 (b)										
Flat Spots	Shall not exceed the appropriate plate flatness and waviness as required by ASTM A6, A20, or A480, as applicable.	See 7.5.4 (c)										
Nozzles	Nozzles (excluding manhole) shall be installed within the following tolerances: Specified projection from outside of tank shell to extreme face of flange: ± 5 mm Elevation of the shell nozzle or radial location of a roof nozzle ± 6 mm Flange tilt in any plane, measured on the flange face: ± 1/2 degree for nozzles greater than NPS 12 in. nominal diameter. ± 3 mm at the outside flange diameter for nozzles NPS 12 and smaller. Flange bolt hole orientation ± 3 mm.	See 7.5.6										
Shell Manhole	Manhole shall be installed within the following tolerances: Specified projection from outside of shell to extreme face of flange, ± 13 mm. Elevation and angular location, 13 mm. Flange tilt in any plane, measured across the flange diameter, 13 mm.	See 7.5.7										

Examination and Testing of Sump Welds

Sump welds in API storage tanks, as defined by API 650, are crucial for ensuring the integrity and leak tightness of the bottom of the tank. These welds, particularly those connecting the sump plate to the tank bottom and sump itself to the shell, must adhere to specific requirements for materials, welding procedures, and inspection to prevent potential leaks and ensure long-term service.

Sump welds undergo mandatory visual inspection for defects and leaks prior to installation, executable in shop or field conditions, with acceptance per Section 8.5.

All sump joints require verification via the methods outlined in Section 7.3.4, such as vacuum testing, tracer gas detection, or liquid penetrants, ensuring hydraulic isolation before backfilling or shell erection. These examinations precede hydrostatic proofing, mitigating the risks of subsurface pinholes or incomplete fusion that could compromise the bottom integrity during service.

Shell-to-Bottom Welds

Shell-to-bottom fillet welds require rigorous examination of the initial inner pass prior to outer weld deposition, employing purchaser-approved non-destructive methods to confirm fusion integrity.

Approved Inside Visual Inspection Methods

Visual inspection is accompanied by magnetic particle testing or liquid penetrant application, either solvent-based with developer dwell exceeding one hour or water-soluble across the joint, alongside high-flash-point oil wicking after four hours or vacuum box bubble detection [20].

Procedural Safeguards

These protocols circumferentially detect cracks, lack of fusion, or porosity with magnetic particle flexibility permitting weld-side precedence, ensuring annulus leak tightness before subsequent shell course erection.

NON-DESTRUCTIVE TESTING IN FABRICATION OF STORAGE TANKS

NDE encompasses techniques that assess material and weld integrity without impairing functionality, enabling precise flaw characterization in storage tanks.

Role in Oil and Gas Assets

In pipelines, refineries, and API 650 tanks, NDE detects minute discontinuities that can escalate to leaks or ruptures, averting ecological incidents and economic disruptions, while safeguarding stakeholders [21, 22].

Application Specificity

Requirements vary by joint type, alloy group, and operating environment, with mandatory radiographic, ultrasonic, or penetrant testing integrated into fabrication, hydrotesting, and API 653 in-service evaluations to maintain mechanical reliability.

Non-destructive testing is a technical means to detect weld defects in large vertical tanks and judge whether the weld is qualified using the characteristics of sound, light, magnetism, and electricity without damaging the tested object [23]. Welds are inspected visually, radiographically, or using ultrasonic techniques to ensure compliance with the joint efficiency factors. The Fourteenth Edition of API 650 (August 2025) introduced enhanced flexibility in NDE options, permitting ultrasonic testing (UT) as an alternative to radiography and liquid penetrant testing (PT) in place of vacuum box methods.

Pre-Acceptance Verification Protocols

Surface inspections, dimensional checks, and NDE occur prior to final tank approval, with Annex T consolidating the requirements, acceptance criteria, examiner qualifications, and procedure specifications for standardized compliance.

Fabrication NDE Applications

Industries fabricating API 650 tanks deploy these methods, including visual, ultrasonic, dye penetrant, magnetic particle, and radiographic techniques, during and post-weld processes to validate joint integrity across bottoms, shells, and roofs (Figure 5).

- Visual Examination
 - Direct Visual Examination by direct eye
- Radiography Testing
- Liquid Penetrant Examination
- Ultrasonic Testing
- Ultrasonic Thickness Check
- Magnetic Particle Testing
- Vacuum Box Testing
- Hydrostatic Testing
- Pneumatic Testing

Visual Examination

Visual Examination is the first-line defense against welds. Visual inspection serves as the cornerstone method for evaluating ASTs, offering simplicity, economy, and accessibility for routine assessment.

Execution and Enhancements

Experienced inspectors conduct direct surface examinations under controlled lighting with a minimum of 1000 lx, employing unaided vision or remote cameras with specialized illumination to capture high-resolution images of welds, plates, and appurtenances.



Figure 4. Storage tank roof.

Photo courtesy: On-site inspection at TEMA India Private Limited, Panoli, Gujarat, India.

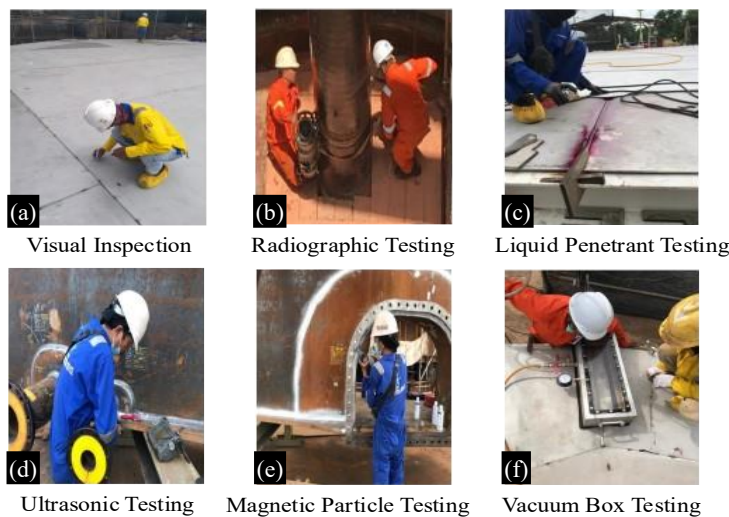


Figure 5. (a) to (f) Various NDT methods are employed during storage tank inspection.

API 650 Mandates

Pre-installation scrutiny of the shell and roof plate edges detects laminations, triggering ultrasonic extent mapping; repairs via edge gouging seal defects up to 75 mm long by 25 mm deep, while larger flaws necessitate full excision or plate rejection.

Weld Imperfection Criteria

All butt welds undergo visual checks for cracks, arc strikes, undercut, porosity, and fusion, which require clean, ripple-free surfaces under bright light to facilitate subsequent NDE, with smoothing of the internal shell welds and burr removal ensuring compliance.

API 650 Visual Testing Acceptance Criteria

The visual examination acceptance criteria per API 650 Section 8.5.2 define permissible weld imperfections to ensure structural soundness without compromising serviceability.

Crack and Arc Strike Prohibitions

No crater cracks, surface discontinuities, or arc strikes occurred within or adjacent to the completed joints, eliminating fatigue initiation sites under cyclic hydrostatic or thermal loading.

Undercut and Porosity Limits

Specific limits were applied to the undercut depth. For vertical-butt welds, the undercut should not exceed 0.4 mm. Horizontal butt welds allow for a slightly deeper tolerance not exceeding 0.8 mm. For

welds with nozzles, manholes, cleanout openings, and other permanent attachments, the undercut depth should not exceed 0.4 mm.

The surface porosity also has defined criteria. For any weld length of 100 mm, there should not be more than one porosity cluster, where a cluster signifies one or more pores. Moreover, the diameter of any individual porosity cluster must not exceed 2.5 mm per 100 mm length. Excessive porosity in welds compromises the mechanical strength through gas entrapment during solidification, necessitating strict visual limits per API 650.

Reinforcement Thickness Constraints

Excess cap height beyond limits, typically 3 mm for plates under 25 mm, requires grinding to contour, ensuring uniform corrosion allowance and NDE accessibility without the mandatory removal of compliant profiles.

The butt weld caps on both plate faces adhere to specified maxima, typically 3 mm for thicknesses less than 25 mm, preventing stress risers and facilitating NDE interpretability while maintaining corrosion allowance uniformity, as shown in Table 3.

API 650 Section 8.5.2 permits weld reinforcement to remain unless it exceeds the specified maximum thickness or obstructs radiographic interpretability per Section 8.1.3.4 [2].

Standard Compliance Imperative

Visual criteria underpin the fitness-for-service verification of low-pressure tanks containing crude, chemicals, or intermediates, where adherence averts progressive degradation, leakage propagation, and operational disruptions.

During visual inspection, certain weld defects were not strictly permitted. Cracks, including both craters and surface cracks, are unacceptable. Similarly, arc strikes found on or adjacent to the welded joint were not tolerated and must be removed.

Furthermore, a smooth transition between the weld and plate surface is mandatory. This requirement aims to prevent sharp angles that can create stress concentration points, thereby enhancing the overall durability of the weld and reducing the likelihood of fatigue failure.

Misalignment Tolerances

Vertical joints in plates exceeding 16 mm thickness permit misalignment up to 10% of nominal thickness or 3 mm maximum, reducing to 1.5 mm for thinner sections, while horizontal butts constrain upper plate projection to 20% of its thickness (capped at 3 mm, or 1.5 mm below 8 mm).

Taper and Finish Requirements

Discontinuous thickness transitions demand 4:1 tapers, weld toes blend seamlessly without abrupt angles, and flange raised faces achieve 3.2–6.3 μm roughness to optimize gasket sealing under low-pressure cycling.

Fillet Welds

Fillet welds in API 650 storage tanks underwent mandatory visual examination, with acceptance and repair criteria delineated in Section 8.5.

Leg Length Measurement

Unlike groove welds, fillet welds are evaluated based on leg length rather than throat penetration, ensuring adequate shear capacity at the lap and T-joints under eccentric loading.

Shell-to-Bottom Attachment

The lowest shell course to the bottom plate connection adheres to the minimum leg dimensions specified in Section 3.1.1, guaranteeing leak tightness and hoop stress transfer during hydrostatic filling and service, as listed in Table 4.

Radiography Testing

Radiographic testing (RT) evaluates full-penetration butt welds in storage tank shells, annular plates, and flush connections, confirming the fusion integrity per API 650 Section 8.1 requirements in Figure 6.

Application Scope

RT targets vertical and horizontal shell seams, lower course-to-bottom transitions, and roof ring joints, with examination extent scaled by plate thickness, joint orientation, and design pressures to detect volumetric flaws, such as porosity or inclusions.

Radiography Procedural

Conducted immediately after welding completion, RT follows the ASME Section V Article 2 protocols, ensuring complete penetration and fusion without delays that could mask progressive cracking under hoop tensile loads [24].

RT verified complete penetration and fusion in designated butt welds of API 650 storage tanks, targeting critical shell-to-shell, shell-to-bottom, and shell-to-roof junctions.

Examination Extent

Testing coverage, typically full for lower courses and spot for upper courses, varies with plate thickness, joint orientation, and tank configuration, ensuring volumetric flaw detection without excessive radiation exposure.

Key RT Requirements

- *Shell welds*: Radiography is required for butt welds in the shell, both vertically and horizontally.
- *Annular plate Welds*: Radiography is required for butt welds on annular plates (bottom plates).
- *Shell-to-bottom welds*: RT is required for the joint between the shell and bottom plates, including annular plate welds.
- *Shell-to-roof welds*: RT may be required for shell-to-roof connections, particularly for certain roof designs.
- *Insert plates*: Radiography is required for insert plates.
- *Dissimilar thickness welds*: Special consideration is given to welds involving plates of significantly different thicknesses, with specific requirements for RT. RT always considers thinner plates [25].

Extent of Radiography

API 650 Section 8 specifies the RT extents for butt welds, calibrated to plate thickness, welder output, and joint geometry to ensure consistent quality, as shown in Figure 7.

Spot Radiography Protocols

For plates ≤ 10 mm thick, one RT shot examined the first 3 m of each vertical joint per welder and thickness, followed by one per 30 m thereafter, regardless of the operator, including $\geq 25\%$ at vertical-horizontal intersections (minimum two per tank) and one random shot in the lowest course.

Quality Escalation Measures

Failure of additional spot radiographs in vertical seams mandates complete seam RT, safeguarding fusion integrity under base hydrostatic tension across the shell courses.

API 650 Section 8.1.2.2.b escalates the RT requirements for shell plates between 10 and 25 mm thick to address heightened hoop stress concentrations.

Enhanced Intersection Coverage

Beyond the baseline spot RT, all vertical-horizontal joint junctions receive full radiography, with each film capturing ≥ 75 mm of vertical weld and 50 mm along horizontal seams on either side of the intersections in Figure 8.

Lowest Course Intensification

Each vertical joint in the bottom course mandates two spot radiographs, one positioned as low as feasible near the shell-to-bottom weld and the other at a random elevation, to verify fusion under maximum hydrostatic tension.

API 650 Section 8.1.2.2 mandates full RT for vertical shell joints exceeding 25 mm thickness, along with complete coverage of all vertical-horizontal intersections.

Thick Plate Requirements

This comprehensive RT ensures volumetric integrity under peak hydrostatic tension, capturing potential slag inclusions, cracks, or lack of fusion that can propagate circumferentially in lower courses.

Insert Plate Protocols

Peripheral butt welds surrounding thickened inserts or nozzle reinforcements, extending less than the adjacent shell height, underwent 100% RT to validate fusion around flush cleanouts, manholes, and flush connections.

Elevated Design Triggers

Client-specified high-stress designs or elevated allowable stresses trigger full RT across shell seams, annular plate joints, and flush butt welds, thereby prioritizing rupture prevention in critical services.

Shell butt welds (vertical and horizontal) require spot radiography using API 650, as shown in Figure 5. The standard specifies the percentage of welds to be radiographed (e.g., 100% for bottom plate joints and 50% for annular plate joints). It also dictates the location of the spot radiographs along the weld seams (e.g., first a few meters, then periodically along the run).

Dished ends should be seamless or 100% radiographed when made from more than one piece. API 650 selectively exempts certain non-critical welds from RT, concentrating examinations on high-stress butt joints while imposing surface-finish constraints at RT locations.

Exempted Weld Features

Roof plate seams, bottom laps, roof-to-top-angle fillets, and shell-to-bottom connections bypass RT with minimum shot counts and positions dictated by Section 8 requirements, judged against ASME Section VIII Div. One UW-51(b) criterion using clear penetrameter visibility [26].

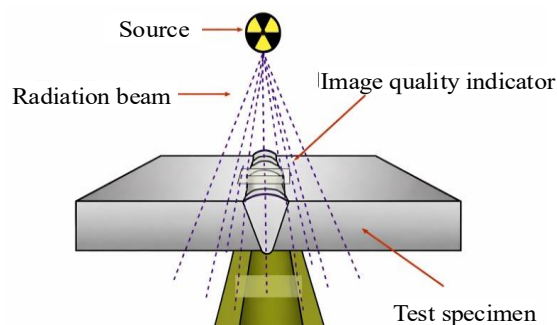


Figure 6. Schematic of radiography testing.

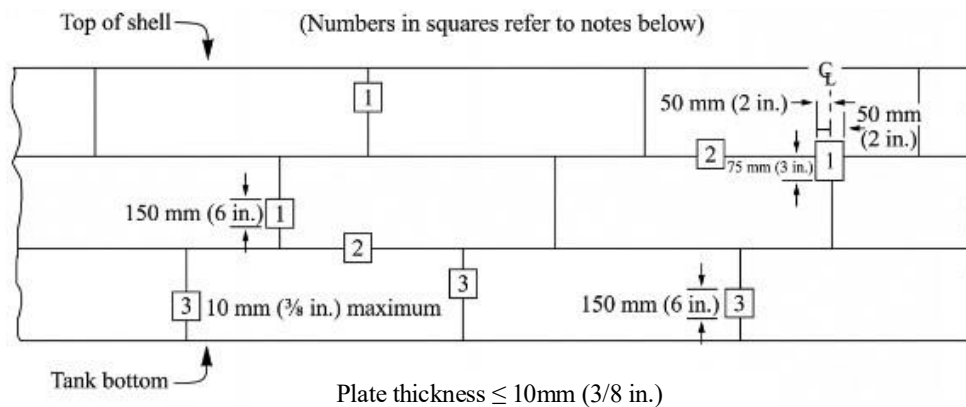


Figure 7. Radiographic requirements for tank shells “(API 650, Section 8.1.2.2, 2025)”.

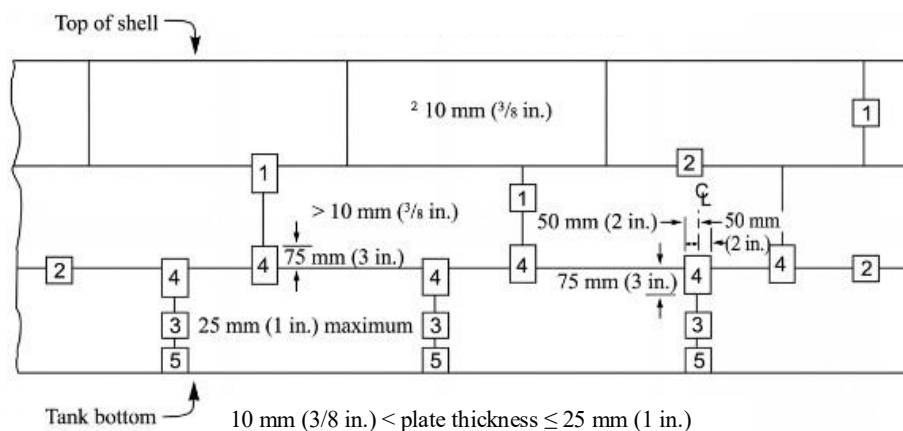


Figure 8. Radiographic requirements for tank shells “(API 650, Section 8.1.2.2, 2025)”.

Special Feature Radiography

Shell/external roof manholes and nozzles exceeding 250 NB, plate-fabricated pipes, and heating coil butts require 100% RT to ensure fusion integrity under thermal cycling and pressure transients.

Reinforcement Contour Limits

At RT sites, weld crowns maintain flush or uniformly capped profiles that do not exceed the specified maxima, typically 3 mm for plates under 25 mm, to facilitate film interpretability without mandatory grinding of compliant geometries, as shown in Table 5.

Radiographic acceptance standards for API 650 welds distinguish linear from rounded indications by applying the ASME Section VIII Division 1 criteria to ensure flaw tolerability under service loads.

Linear and Rounded Indication Limits

Linear defects adhere to UW-51 thresholds, whereas rounded discontinuities follow Mandatory Appendix 4 guidelines, rejecting clusters or elongations that exceed the size, spacing, or density limits for the examined thickness.

Radiographer Certification

Operators must hold manufacturer certifications compliant with the ASNT SNT-TC-1A and supplements, verifying competency in exposure techniques, film processing, and interpretation to uphold examination reliability.

For radiographic reports according to API 650, details such as the project ID, tank ID, date, location, radiographic test procedure, weld joint details, radiographic findings, and acceptance/rejection status of

each weld, along with the inspector's name and signature, should also be included. Manufacturers must generate a comprehensive radiograph map documenting precise locations and film identification codes for all radiographic examinations conducted on tank welds.

Documentation Purpose

This mapping facilitates traceability, enabling purchaser verification of compliance with API 650 Section 8.1 shot extents, welder performance tracking, and correlation of film results to specific joint segments during quality audits.

Record Integration

Maps are integrated into as-built drawings and inspection dossiers, supporting future API 653 baseline assessments and fitness-for-service evaluations by preserving spatial flaw distributions across shell courses and critical intersections.

Liquid Penetrant Examination

Liquid penetrant testing (LPT) is an economical non-destructive method for detecting surface-breaking discontinuities in ASTs.

Technique Fundamentals

This process employs the capillary action of low-viscosity penetrants to infiltrate cracks, porosity, or laps, followed by developer drawback revealing indications under white light or UV for nonfluorescent variants.

Tank Application Relevance

LPT verifies fillet welds, nozzle-to-shell fusions, and repair sites per API 650 Section 8.3 alternatives to vacuum box testing, ensuring leak paths or fatigue origins remain identifiable prior to hydrostatic commissioning.

Importance of Liquid Penetrant Examination

- *Leak tightness:* Liquid penetrant examination (LPE) helps ensure that the tank welds are free of leaks, which is crucial for preventing product loss and environmental contamination.
- *Structural integrity:* By identifying and addressing surface defects, LPE helps ensure the structural integrity of the tank and prevents potential failures.

Table 3. Permissible maximum reinforcement during visual testing.

Plate thickness (mm)	Maximum reinforcement thickness (mm)	
	<i>Vertical joints</i>	<i>Horizontal joints</i>
≤13	2.5	3
>13 to 25	3	5
>25	5	6

Table 4. Minimum size of fillet weld.

S. N.	Nominal Thickness of Shell Plate (mm)	Minimum Size of Fillet Weld (mm)
1	5	5
2	> 5 to 20	6
3	> 20 to 32	8

Table 5. Maximum thickness of reinforcement.

S.N.	Plate thickness (mm)	Maximum thickness of reinforcement (mm)
1	≤13	1.5
2	>13 to 25	2.5
3	>25	3

- *Quality control:* LPE is a key part of the quality control process for API 650 tank fabrication, ensuring that the tank meets the required standards.

In API 650 storage tank fabrication, LPE is a crucial non-destructive testing method used to detect surface-breaking defects, such as cracks, laps, and porosity. This method is specified for various tank components and weld joints to ensure structural integrity and leak tightness. The LPE requirements are detailed in API 650 with specific guidelines for application, acceptance criteria, and reporting. LPE can be employed in stainless steel, carbon steel, or non-magnetic materials for detecting surface cracks [27].

Components and Welds Subject to LPE

- *Shell-to-bottom weld:* The weld connecting the tank shell to the bottom plates is a critical area and often requires LPE, particularly for the root pass.
- *Nozzle Welds:* Welds with nozzles attached to the tank shell or bottom were also inspected using LPE.
- *Other welds:* LPE may be specified for other welds based on the tank's design, material, and service conditions, as determined by the manufacturer and purchaser.

LPE Procedure and Requirements

The LPE per API 650 Section 8.4.1 adheres to ASME Section V Article 6 protocols for detecting surface discontinuities in storage tank welds and plates, as shown in Figure 9.

- *Procedure execution:* A low-viscosity penetrant, dyed visible or fluorescent, coats the cleaned surface, infiltrating cracks, porosity, or laps during the specified dwell time; excess is removed, followed by developer application drawing trapped penetrant into indications viewable under white light or UV [28].
- *Discontinuity detection:* This method reveals surface flaws that compromise leak tightness or fatigue resistance in fillet welds, nozzle fusions, and repair zones, enabling rejection or remediation before hydrostatic testing or service entry.

LPT requires meticulous surface preparation, penetrant application, and developer deployment to reliably expose the surface-breaking flaws in storage tanks.

- *Surface preparation essentials:* Test areas require thorough cleaning, degreasing, and drying, including etching, to eliminate contaminants such as oils, scales, or coatings that could mask discontinuities or inhibit capillary ingress.
- *Penetrant and developer sequence:* Visible or fluorescent penetrant coats the prepared surface for a specified dwell time, enabling seepage into cracks or porosity, and excess removal precedes developer application, which extracts trapped penetrant to form visible bleed-out indications under appropriate illumination.
- *Inspection:* The inspected surfaces were examined under appropriate lighting conditions (UV light for fluorescent penetrants) to identify any defects.

Acceptance Criteria

API 650 provides specific acceptance criteria for LPE indications and defines what constitutes rejectable discontinuities. These criteria are based on the size and type of indication. Acceptance for LPE, as per Appendix 8 of the ASME Sec. VIII Div.1 [18]. The acceptance criteria for LPE defects, along with their removal and repair, follow the ASME Section VIII Annex 8 provisions (Paragraphs 8-3 through 8-5), as mandated by API 650 Section 8.4.4.

Defect Evaluation Process

Examiners classify indications according to the ASME criteria, distinguishing relevant flaws from false signals; unacceptable discontinuities prompt weld removal, material repair, or replacement, with retesting ensuring compliance before tank hydrostatic commissioning.

Comprehensive Reporting Requirements

Inspection records must detail the examined areas, penetrant type (visible or fluorescent), dwell duration, developer specifications, and all observed indications (linear or rounded) to support traceability, auditor review, and fitness-for-service evaluation.

Ultrasonic Testing

UT serves as a versatile non-destructive evaluation technique for detecting internal flaws and measuring wall thickness in oil and gas storage tanks according to API 650 and API 653 standards.

UT Principles and Applications

High-frequency sound waves from transducers propagate through tank materials, such as shells, bottoms, or roofs, reflecting off discontinuities such as cracks, corrosion, voids, or laminations. Signal analysis reveals flaw location, size, and thickness variations without material damage.

Laminations Check

Ultrasonic thickness gauges (UTGs) enable precise, portable wall assessments, identifying service-induced thinning or fabrication laminations. Plates with laminations under 75 mm in length or 25 mm in depth permit edge gouging and re-welding, while larger defects require full removal or plate rejection pending purchaser-approved procedures.

Defect Detection

UT is commonly applied to thick materials and welded joints, particularly when RT is impractical because of accessibility or safety constraints. Procedures for UT must align with the ASME Boiler and Pressure Vessel Code, Section V, Article 4, which outlines the detailed requirements for ultrasonic methods for welds.

Minimum Thickness Rules

UT serves as an alternative to RT, specifically for welds where the thinner member exceeds or equals 6 mm in thickness, as specified in relevant code annexes such as ASME provisions for such applications.

Acceptance Standards

The evaluation of UT results follows API 653 guidelines, ensuring that defects are sized and classified against defined limits for tank inspections and repairs. This approach enhances the detection of subsurface flaws, such as cracks or a lack of fusion in volumetric exams, as shown in Figure 10.

Advanced Techniques such as Automated Ultrasonic Testing (AUT) may be used for weld inspection as an alternative to traditional radiography, provided that they meet the requirements of API 650 Annex U [2]. It uses automated sensors to quickly scan and analyze welds, offering faster results with no radiation hazards.

Magnetic Particle Examination

Magnetic particle testing is a non-destructive testing method used to inspect surface and subsurface imperfections in oil and gas storage tanks made of ferromagnetic materials. It is used to detect defects in various parts, such as nozzles, reinforcement pads, and attachments, as shown in Figure 11.

Magnetic particle testing (MPT) utilizes induced magnetic fields to reveal the surface and near-surface discontinuities in ferromagnetic storage tank components.

Field Induction and Particle Response

Direct or alternating current magnetizes the test area, creating flux leakage at flaws that attract fine iron particles, dry powder or wet suspension, forming visible indication patterns aligned with the crack orientation.

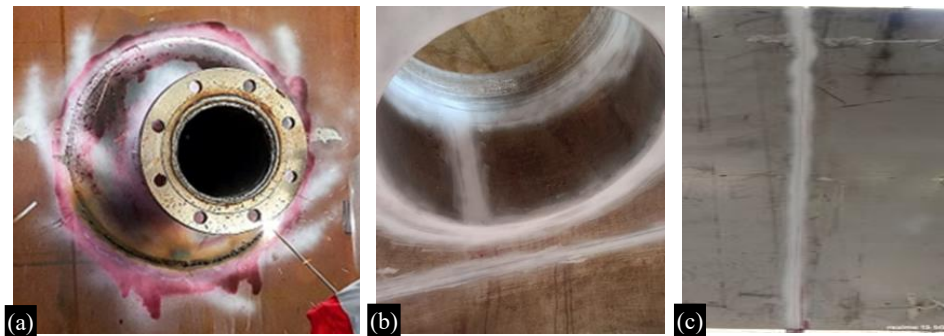


Figure 9. (a) to (c) LPE of welding joints of API 650 storage tanks.

Photo courtesy: Shop inspection at Sparkon Engineers, Galenda, Gujarat, India, and TEMA India Private Limited, Panoli, Gujarat, India.



Figure 10. Thickness checking with an ultrasonic thickness gauge.



Figure 11. Magnetic particle inspection.

Application Advantages

This method excels in detecting tight surface cracks, laps, or seams in tank shells, nozzles, and welds made from carbon steel, enabling the rapid assessment of structural integrity before service or following repairs.

Code Compliance Protocols

The examination adheres to the ASME Section V Article 7 procedures, with mandatory application to annular plate corner welds and critical joints under Section 8.2; acceptance follows the ASME Section VIII Division 1 Appendix 6 criteria.

Defect Evaluation and Documentation

Unacceptable indications trigger repair or removal per ASME Section VIII Division 1 Annex 6 (Paragraphs 6-3 through 6-5); all records capture T-190 essentials from ASME Section V and method-specific T-X90 documentation for traceability and review.

Vacuum Box Test

A vacuum box test was required to ensure leak tightness in 100% of the bottom plate joints. A vacuum box test was required for the lap welds of the bottom plates to ensure no leakage. The test was performed according to API 650 (Section 8.6). Annular to shell plate joints typically use an oil-chalk or vacuum box test on 100% of the seams, as shown in Figure 12.

Vacuum testing shall be conducted as follows.

Vacuum box testing provides a reliable leak detection method for storage tank seams using portable metal enclosures and soap solutions under controlled vacuum pressure.

Equipment and Setup

The standard vacuum box measured 150 mm wide by 750 mm long with a top glass window and sponge-rubber gasket sealing the open bottom against tank surfaces, including valves, gauges, and vacuum sources such as motor manifolds or pumps maintaining 21–35 kPa gauge, or purchaser-specified 56–70 kPa partial vacuum.

Testing Procedure

Operators brush 750 mm seam lengths with soap or linseed oil, apply vacuum for at least 5 s or viewing time, ensuring 50 mm overlap, and observe for continuous bubbles indicating through leaks or bursting foam signaling large openings; 1000 lx minimum illumination supports the evaluation.

Acceptance and Documentation

Unacceptable leaks require repair and retesting; record detailed test coverage, pressures, temperature, light intensity, and results per API 650 Section 8.6.10, for purchaser review.

Pressure Testing: Hydrostatic Test

Hydrostatic testing serves as the final integrity verification for the fabricated storage tanks, confirming leak tightness and structural performance under design pressures after completing all welding and NDE.

Pre-Test Preparation

Temporary attachments on shell courses require removal, followed by magnetic particles or LPE at attachment sites, arc strikes, and any damaged areas; repairs are ground to smooth profiles before water introduction.

Test Execution Protocol

Per API 650 Section 7.3.7, tanks fill gradually with water or non-hazardous liquid to the overflow point, hold for a specified duration under a hydrostatic head, and then undergo visual inspection for leaks, distortions, or settlements, ensuring safe containment capability.

Post-Test Evaluation

The observed deformations or seepage trigger drain-down, root-cause assessment, and remediation, such as weld buildup or shell reinforcement, with retesting confirming compliance before commissioning.

Hydrostatic Testing Requirements in the API 650 Standard

Hydrostatic testing protocols under API 650 Section 7.3.7 mandate execution prior to permanent external piping connections, except fill/drain lines with flexible settlement accommodations, ensuring unobstructed tank performance verification.

Temperature and Water Management

Carbon and low-alloy steel tanks maintain metal temperatures no colder than the design limits shown in Figure 4, with manufacturers heating water as needed to prevent freezing while avoiding thermal shock.

Floating Roof Measurements

Floating roof tanks require pre-flotation and maximum fill height recordings of shell-to-rim annular clearances, documenting dimensional compliance. Heating coils undergo separate pressure tests per engineering specifications, as shown in Figure 13.

1. Water for hydrotests should be potable water with a chlorine content limited to 25 ppm. After testing, the water drained. The standing water was wiped dry (not allowed to evaporate to dryness).
2. The gasket used for hydrotesting of the equipment should have the same specifications as the service gasket, and the fabricator supplies new gaskets for nozzles with blind flanges, apart from spares. The gasket used for the hydro test should not be used for an actual hook-up.
3. The bolt should have an identical allowable stress at room temperature. As used in the design calculations, or they should be the same as the service fasteners.
4. Hydrostatic testing includes tank fabrication with rigorous cleaning, sustained pressure holds, and strict leakage prohibitions to validate the design integrity.

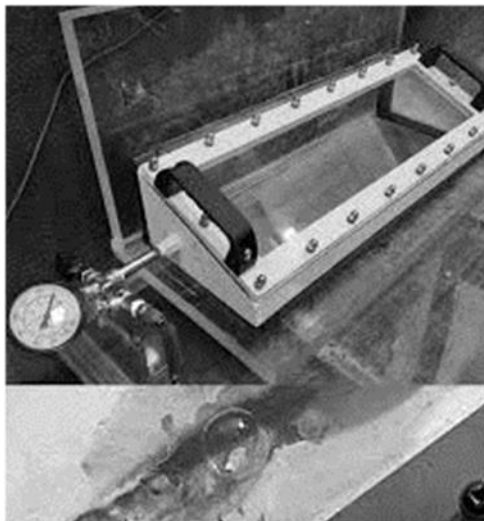


Figure 12. Vacuum box test.



Figure 13. Hydro test—water filling test.

Photo courtesy: Shop inspection at Sparkon Engineers, Galenda, Gujarat, India, and TEMA India Private Limited, Panoli, Gujarat, India.

5. *Pre-Test Cleaning Requirements:* Before final inspection and hydrotest, tank interiors and exteriors underwent complete cleaning to remove slag, scale, dirt, weld splatter, metal pieces, paint, oil, and similar contaminants, ensuring unobstructed flaw detection.
6. *Test Conditions and Duration:* Operators maintain hydrostatic pressure for a minimum of 1 h at temperatures 30°C above MDMT (not exceeding 48°C), with evaluation occurring at least 24 h post-maximum fill, extendable per data sheet specifications, and reject any visible leakage while limiting test pressure to design maximum.

Hydrostatic testing finalizes tank fabrication through comprehensive cleaning, controlled pressure holds, and zero-tolerance leakage criteria to confirm the design compliance.

Cleaning and Preparation

Tank interiors and exteriors were thoroughly cleaned before the final inspection and hydrotest, eliminating slag, scale, dirt, grit, weld splatter, metal fragments, paint, oil, and similar contaminants to enable clear visual assessments.

Test Parameters and Evaluation

Hydrostatic pressure is sustained for at least 1 h with metal temperatures maintained at 30°C above MDMT (not exceeding 48°C); inspection occurs no sooner than 24 h after reaching maximum fill height, extendable per data sheet, prohibiting any visible leakage while capping test pressure at the tank's design limit.

Pneumatic Testing of RF Pads

It is used to assess the integrity of pressure-containing equipment, such as pipelines and vessels, by pressurizing them with gas (usually air or nitrogen) to a specified level, without causing any damage to the system being tested.

Reinforcing plate welds underwent pneumatic leak testing prior to hydrostatic filling, applying up to 100 kPa gauge pressure through tell-tale holes to verify the attachment integrity per API 650 Section 7.3.5.

Test Execution Procedure

Manufacturers pressurize the annular space between the reinforcement plate and shell of each tank shell opening, simultaneously coating all internal and external attachment welds with soap film, linseed oil, or an equivalent leak detection medium to reveal any seepage under load.

Evaluation and Compliance

Bubble formation signal leaks require weld repair and retesting; successful verification confirms that the nozzle reinforcement zones remain leak-tight during subsequent hydrostatic commissioning and service.

Testing of the Roof

Fixed roof seams and pads received mandatory leak testing prior to hydrostatic commissioning, with gas-tight designs undergoing additional verification per API 650 Section 7.3.8.

Seam and Pad Testing

All fixed roof seams undergo 100% air pressure or vacuum box examination, while roof flange RF pads test at 1.5 kg/cm² gauge using soap solution to detect through-wall leaks in attachment welds.

Gas-Tight Roof Verification

Gas-tight roof tests via internal air pressure, not exceeding roof plate weight, with bubble solution on welds or vacuum box per Section 8.6; non-gas-tight roofs with vents receive visual weld inspection unless the purchaser specifies otherwise.

Procedure for Pneumatic Testing of Roof Nozzle RF Pads

- *Preparation:* Ensure that all welding on the nozzle and RF pad is complete and that the area is clean and free of debris. A temporary connection is installed to the RF pad vent hole, which is typically a small opening designed for this purpose. A pressure gauge and controlled air supply were connected to this connection.
- *Pressurization:* Compressed air is slowly introduced into the space between the nozzle neck and RF pad through the vent hole. Pressurize the RF pad to a specified test pressure, often around 5 psig, as per project specifications or API standards API 650. The test pressure was maintained for a designated hold time, typically 10 min.
- *Leak detection:* During the hold time, a soap solution (or other suitable leak detection fluid) was applied to all weld seams of the RF pad and the nozzle connection to the tank roof. The formation of bubbles, which indicates a leak, was visually inspected.
- Effective visual inspection of storage tanks requires a minimum illuminance level of 1000 lx to reliably discern surface anomalies.
- *Evaluation:* The test was considered successful if continuous bubble formation was not observed, indicating a leak-free weld.
- *Repair and retest:* If leaks are detected, the defective weld areas must be repaired by grinding out the defects and re-welding. After repair, the pneumatic test procedure must be repeated for the affected area to confirm the integrity of the repair.
- *Documentation:* Maintain comprehensive records of pneumatic testing, including test pressure and hold time, leak detection results, any repairs performed, and subsequent retest results, relevant drawings, welding, and inspection records.

NON-DESTRUCTIVE EXAMINATION METHODS COMPARISON IN FABRICATION OF API 650 STORAGE TANK

Each method offers unique benefits and is specified by API 650 in relevant clauses, ensuring comprehensive quality and safety control during storage tank fabrication, as shown in Table 6.

Weld defects exceeding allowable limits must be repaired to ensure safety and code compliance. As per the API, 650 storage tanks must be inspected every two years [29].

Table 6. Comparison of non-destructive examination (NDE) methods in the fabrication of API 650 storage tanks with typical applications, and major advantages.

NDE method	Typical applications	Advantages	API 650 clause reference
Visual inspection (VT)	General weld and surface integrity checks	Quick, low cost, effective for obvious defects	8.1
Radiography (RT)	Internal discontinuity detection in welds	Permanent record, deep penetration	8.4.1, 8.4.4, 8.4.6
Liquid penetrant testing (PT)	Locating surface-breaking flaws on non-ferrous components	Good for non-magnetic materials, fine cracks	8.4.3
Ultrasonic testing (UT)	Measuring weld thickness and flaw detection in the weld volume	Detects internal flaws, quantifies geometry	8.4.6, 8.5.2
Magnetic particle testing (MT)	Detecting surface/subsurface cracks in ferrous welds	Sensitive to small cracks and discontinuities	8.4.2
Vacuum box testing (VBT)	Examining tank bottom seams for leakage	Practical for quickly detecting leaks	8.5.4
Leak testing (LT)	Tank bottom welds and nozzles	Directly verifies fluid containment integrity	8.5.6, 8.5.7

Case Study: Draining and Drying of Heating Coil After Hydrotesting for Bulk Additive Tank Fabricated as Per API 650

TEMA India Limited is situated in Panoli, which is near the industrial areas of Ankleshwar, Bharuch, and Gujarat. India. The fabrication of a new atmospheric storage tank (six nos. per API 650 (14th ed.) was completed within the stipulated time schedule to match the delivery date. The Client was Shell India Markets Private Limited, and the Project Management Consultant was Tata Consulting Engineers Limited for their Basic Design and Engineering Package (BDEP) Services for Shell Everest at Taloja, Maharashtra.

The tank was a fixed roof with a conical bottom. The operating capacity of the tank was 46 m^3 , considering a density of 1100 kg/m^3 at its storage temperature. Steam was used as the heating medium for the storage tank. An internal steam heating coil with a size of 50 NB is provided for attaining the storage temperature. The helical coil was to be provided at the lowest possible level between the LL and NLL of the tank according to technical specifications. The length of the coil was 73.16 m. These two turns were provided below the tank BTL.

Challenges and Solutions

In the context of contamination and water quality, the challenges include scaling deposits from hard water, rust formation after testing, bacterial growth in residual water, and difficult drying for complex coil geometries. Because the position and rotation of the tank cannot be changed because of nozzles and other welded attachments, the complete draining and drying process must be performed in the same tank position. The solutions selected were the use of treated, demineralized, or inhibited water to prevent corrosion, and dry air + nitrogen purge was applied after draining to prevent internal rust. Early action immediately after hydrotesting ensured complete drying of the coil. After complete draining and drying, the dew point was checked from both the lets, and it was found to meet the requirements shown in Figure 14.

CONCLUSION

NDE methods enable a comprehensive evaluation of storage tank integrity without compromising structural components. These techniques detect subsurface flaws, corrosion, and material degradation at incipient stages, supporting proactive maintenance in tanks that handle hydrocarbons, chemicals, and water. NDE facilitates risk prioritization, extends service life through targeted repairs, and aligns with standards, such as API 650, for periodic integrity verification.



Figure 14. Hydrotesting of the coil inside the storage tank.

Photo courtesy: Shop inspection at TEMA India Private Limited, Panoli, Gujarat, India.

Noncompliance can result in safety hazards, environmental damage, and legal consequences. Industries must adhere to these standards to protect their assets and the environment. NDE practices should be aligned with API 650 to verify compliance with these design parameters, thus safeguarding tank integrity for various services. The outcome emphasizes that adherence to API 650 welding and NDE requirements significantly reduces the structural failure risk in petroleum storage applications. API 650 emphasizes the importance of periodic inspections, examinations, and testing to assess the condition of a tank throughout its service life.

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Conflicts of Interest

Author Kamal Dhandha was employed by TUV India Private Limited, TUV NORD Group. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

API	American Petroleum Institute
NDE/NDT	Non-Destructive Examination/Non-Destructive Testing
EPC	Engineering, Procurement, and Construction
DMT	Design Metal Temperature
AST	Aboveground Storage Tank
VT	Visual Testing/Inspection
RT	Radiographic Testing
UT	Ultrasonic Testing
PT	Penetrant Testing/Liquid Penetrant Testing
MT	Magnetic Particle Testing
VBT	Vacuum Box Testing
LT	Leak Testing
RF Pad	Reinforcement Pad
UTM	Ultrasonic Thickness Measurement
AUT	Automated Ultrasonic Testing
SMAW	Shield Metal Arc Welding
WPS	Welding Procedure Specification
PQR	Procedure Qualification Record
ASME	American Society of Mechanical Engineers
MDMT	Minimum Design Metal Temperature
NB	Nominal Bore (pipe diameter designation)
MPT/MPI	Magnetic Particle Testing/Inspection
LPE	Liquid Penetrant Examination
BTL	Bottom Tan Line
LL	Lowest Level
NLL	Normal Liquid Level

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