*Research Journal of Forensic Sciences* _____________________________________________ ISSN 2321–1792
Vol. **14(2),** 27-33, July **(2026)** *Res. J. Forensic Sci.*

# Mechanical Explosion arising from in-situ Hydrogen generation in a fabricated cylinder: Fundamentals and Forensic awareness

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**Available online at: www.isca.in, www.isca.me**
Received 16th May 2026, revised 13th June 2026, accepted 5th July 2026

## Abstract

*Improvised metallic cylinders are gradually being misused for the generation of chemical gas without conformity to standard pressure-vessel design. The significant gas pressure and heat is generated by hydrogen formed from aluminium–alkali reactions, which creating conditions that may exceed the structural capacity of non-engineered vessel/containers. Present article describes the basic chemistry of generation of hydrogen using caustic soda and aluminium, the mechanism of pressure development along with the principles of engineering regulating safe pressure-vessel design. The practical and real life cylinder failure is presented as an anonymised case study. The detailed analysis reveals that the stress developed in present scenario that the fabricated aluminium vessel possessed insufficient wall thickness and weld reliability for the pressure potentially generated. The main aim of the present research article is to suggest the public and enforcement awareness concerning the dangers of using uncertified fabricated cylinders for the production of hydrogen for many purposes and highlights the requirement of the legal compliance and safety education. The present work inspected the structural integrity and failure potential of a fabricated aluminium cylinder repurposed for the hydrogen gas storage and generation.*

**Keywords:** Forensic Science, Hydrogen, Explosion, Cylinder Safety.

## Introduction

Hydrogen is considered as one of the most propitious substitutes for conventional energy sources such as oil and natural gas. It is highly abundant, inexhaustible and during use it will not greenhouse gas emissions. The considerable research is increased towards safe storage and transportation of hydrogen due to these environmental benefits which are critical for its practical application in fuel cells and fuel systems. Several methods are used to store the hydrogen such as cryogenic liquid tanks, polymer- or composite-based materials, metal hydrides, and high-pressure gaseous cylinders[1,2].

Hydrogen gas ($H_2$) is the lightest, abundant element, a colorless, odorless, tasteless, and highly flammable gas, crucial as a clean energy carrier and in industrial processes like refining and fertilizer production. However, the ease of production can create a false sense of safety, particularly when such reactions are conducted in improvised containers not intended for gas storage. Gas cylinders appear like simple containers, but their building is crucial due to their performance. The materials used affect not only the lifespan of the cylinder but also its ability to withstand pressure and environmental conditions[3].

Approved gas cylinders and pressure vessels are not simply manufactured and put into service; they must first pass through rigorous engineering design, careful selection and testing of materials, non-destructive examination of welds, and hydrostatic pressure testing to confirm structural integrity. Compliance with internationally recognized codes—such as ASME Section VIII, ISO 9809, and applicable national gas-cylinder regulations—ensures that parameters like material strength, wall thickness, heat treatment, safety margins, and allowable working pressure meet strict safety requirements.

These precautions are necessary because compressed gases subject the vessel to significant mechanical loads, and any structural failure can produce explosive rupture, high-velocity fragments, and severe injuries[4].

Unlike certified pressure vessels, homemade or improvised cylinders typically do not comply with established safety and design standards. The properties of the materials used are often uncertain, weld quality may be unverified, structural design can be inadequate, and essential safety components such as pressure-relief devices are usually absent. If hydrogen is produced rapidly within such a container, the internal pressure may increase faster than the vessel can withstand, leading to sudden and catastrophic rupture. Improvised cylinders also lack traceability of materials, formal inspection of joints, protective valves, and adequate safety margins in design.

This paper discusses these hazards in clear technical terms and presents an anonymized rupture incident to highlight the risks and promote public-safety awareness[5,6].

## Materials and Methods

**Fundamentals of Hydrogen Generation:** Hydrogen gas is often generated from natural gas or water via electrolysis, though it's scarce as a free gas on Earth and must be produced primarily through fossil fuel-based methods like steam methane reforming (SMR) and greener methods such as electrolysis of water or biomass gasification, new pathways like methane pyrolysis and direct solar water splitting. SMR splits natural gas with steam, releasing $CO_2$, while electrolysis uses electricity to split water ($H_2O$) into $H_2$ and $O_2$, with green hydrogen using renewable electricity for a low-carbon process. Microorganisms such as bacteria and algae can produce hydrogen through biological processes. However, there are methods to prepare hydrogen gas such as easily available chemical process which includes metallic aluminum and aqueous alkali medium but compromising the safety hazardous particularly when such reactions are conducted in improvised containers or fabricated cylinders which are not intended for gas storage. Reacting aluminum with sodium hydroxide (NaOH) solution produces hydrogen gas and sodium aluminate ($NaAl(OH)_4$), a simple method utilizing aluminum's amphoteric nature. Aluminium metal is normally protected by a thin oxide layer on its surface, which prevents further reaction with air or water. Sodium hydroxide dissolves this oxide layer and exposes the underlying aluminium, allowing it to react continuously with water. The overall reaction produces hydrogen gas and soluble aluminate compound as mentioned in scheme-1[7-9].

$$2Al + 2NaOH + 6H_2O \rightarrow 2NaAl(OH)_4 + 3H_2 \uparrow$$

**Scheme-1:** Preparation of soluble aluminate compound.

Aluminium acts as the source of hydrogen atoms *via* water, sodium hydroxide acts as a catalyst and oxide remover reaction was accompanied by excessive heat generation producing hydrogen gas continuously as long as reactants are remaining, as temperature rises rate of the reaction increases with the expansion of gas and increases pressure inside a closed container. Thus, every mole of aluminium produces 1.5 moles of hydrogen gas. The reaction also releases heat, increasing gas temperature and pressure. Pressure rise is governed by the ideal gas law, and asmallrise in temperature could renders pressure escalation.

$$P = \frac{nRT}{V}$$

If the container or the cylinder engineering conditions are not followed in terms of quality, strength and the volume, there will be a major chances of catastrophic explosion causing severe damages, conditions such as small volume or the blockage of outlet causes expeditious rise in pressure. Since the reaction accompanies with the excess of heat, the internal temperature increases, further increases the pressure inside the cylinder or container. This combination of heat and gas expansion makes closed-system production of hydrogen extremely hazardous in fabricated vessels.

**Engineering Considerations in Cylinder Safety:** Gas cylinders appear like normal and simple containers, but their building is crucial to their working and principle. The ability to withstand the pressure of the container mainly depends on the materials and lifespan of the cylinder. One of the most widely used materials are steel in cylinders are well known for their strength and stability, which means they can manage heavy-duty use without any impact on safety and ideal for the industry standard for gas cylinders. It is considered as reliable choice for any industry due to its durability, strength, and ability to withstand high pressures. Aluminium cylinders, popular for their portability and corrosion resistance, can facilitate your operations where frequent movement is a challenge. Their lightweight nature, compared to steel, can significantly ease the process of moving cylinders around[10,11].

**Stresses inside a Gas Cylinder:** When gas pressure acts on the inner walls of a cylinder, it creates mechanical stresses within the metal. Two major stresses develop: i. Hoop (circumferential) stress-trying to split the cylinder open lengthwise, ii. Longitudinal stress -trying to pop the ends off the cylinder.
The governing stresses in a cylindrical vessel are:

$$\sigma_h = \frac{PD}{2t} \ \& \ \sigma_l = \frac{PD}{2t}$$

Where: $\sigma_h$ is hoop stress, $\sigma_l$ is longitudinal stress, P is internal pressure, D is cylinder diameter and t is wall thickness.

The hoop stress is approximately twice as large as the longitudinal stress. Therefore, when cylinders fail due to pressure, they typically split along the length-the walls tear open like a tin canister, this pattern was also observed in the present case as shown in Figure-1[12-14]. The material must have enough thickness and strength to resist these stresses at the highest safe operating pressure. Certified vessel designers calculate this precisely. Fabricated vessels do not.

**Why standards require thick walls and tested welds:** Certified gas cylinders use carefully controlled alloys and are often seamless. If welds are present, they must be tested because welded joints are normally weaker than the surrounding metal. Any defect such as porosity, slag inclusion, incomplete fusion, or cracking becomes a weak point where failure begins. Certified cylinders must withstand pressures greater than or equal to 1.5×working pressure with safety factors approximately greater than or equal to 3 on ultimate strength. Improvised welds substantially decrease permitted stress due to welds, defects, porosity, and lack of radiographic testing[15].

## Results and Discussion

**Anonymised Case study: Mechanical rupture of fabricated aluminium cylinder:** An aluminium cylinder as shown in Figure-2,3 represents the failure of cylinder and examined in a forensic-engineering circumstances. The following measured parameters were recorded.

**Figure-1:** Remnants of exploded cylinder.

**Table-1:** Physical measured parameters of the aluminium cylinder.

| Parameter | Physical measurement/ description |
|---|---|
| External diameter ($D_o$) | 98 mm |
| Internal diameter ($D_i$) | 92.8 mm |
| Internal radius (r) | 46.4 mm |
| Wall thickness (t) | 2.6 mm |
| Cylindrical body length | 49 cm |
| Total length including domed ends | ~71 cm |
| End caps type | semi-ellipsoidal |
| Material | aluminium |
| Weld details | 2 circumferential welds + 1 longitudinal seam |
| Empty weight | 14.52 kg |

The cylinder fragments observed in above rupture appears like ductile tearing and major deformation, consistent with mechanical over-pressurization rather than an energetic explosion. The walls were peeled and stretched rather than shattered. This describes that internal gas pressure was surpassed the limit of strength of the thin aluminium shell and welds. No soot, scorching, or detonation marks were observed and which further suggest the mechanical failure.

**Stress and Burst-Pressure Estimation:** As mentioned in the parameters of the cylinders, the cylinder diameter (98 mm) is very large compared with the wall thickness (2.6 mm) and these parameters behaves as a thin-walled pressure vessel. In such vessels, most of the load is carried by the wall material itself, with very little structural redundancy.

**Figure-2:** Ideal aluminium cylinder.

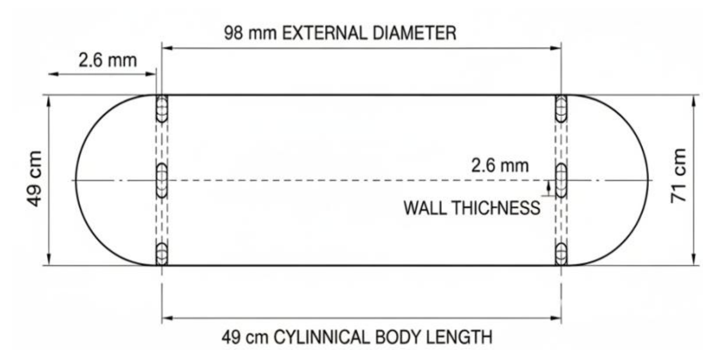


**Figure-3:** Cylinder structure parameters.

**Thin-Wall Validity Check:** Before employing the theory of thin-walled pressure vessel, it is crucial to verify whether the normal LPG cylinder geometry meets the thin-wall criterion. This theory assumes that the wall thickness of the cylinder is small compared to the internal radius since the stress distribution over the wall thickness is uniform. A widely accepted engineering rule-of-thumb states that a pressure vessel may be treated as thin-walled when the ratio of the internal radius (r) to the wall thickness (t) is greater than 20.

$$\frac{D_i}{t} = \frac{92.8}{2.6} \approx 35.6 \;(Which\, is\, greater\, than\, 20)$$

In the present scenario, the internal radius of the cylinder was measured from the internal diameter and the while the wall thickness was measured using direct physical measurements at multiple places to account for any differences and then the ratio was computed. As the calculated value exceeded 20, the cylinder clearly satisfied the thin-wall criterion.

**Allowable strength assumption:** The aluminium used in the fabricated cylinder likely does not have the same strength as industrial pressure-vessel aluminium alloys. Because this is a fabricated aluminium cylinder with welds and unknown alloy/heat-treatment, it is unsafe and unrealistic to assume the ultimate strength of aluminium (≈ 250–300 MPa). Additionally, because there were three weld seams, the effective strength of the structure would be even lower. For safety analysis, a conservative allowable strength value of ~130MPa is appropriate.

**Estimated Burst Pressure:** The burst pressure of a thin-walled cylindrical LPG vessel represents the internal pressure at which the cylinder wall can no longer safely resist the induced circumferential (hoop) stress and catastrophic rupture occurs[16]. For thin-walled cylinders where D/t>20, the hoop stress is considered uniform across the wall thickness and is calculated using the classical pressure vessel relationship:

$$\sigma_h = \frac{Pr}{t}$$

Where: $\sigma_h$-hoop stress (MPa), P- internal pressure (MPa), r-internal radius (m), t-wall thickness (m).

$$P = \frac{\sigma_h \times t}{r} = \frac{(130\,MPa)(0.0026m)}{0.0464m}$$

$$P = 7.28\,MPa$$

So the estimated burst pressure is: $P = 7.28\,MPa = 73bar$

This value represents the pressure at which hoop stress in the shell wall reaches the allowable tensile capacity of the aluminium material. In practice, failure may occur at lower pressure because: i. welds reduce strength significantly (sometimes to 50–60% of parent metal), ii. internal pressure pulsation produces fatigue, iii. semi-ellipsoidal ends introduce biaxial stress, iv. longitudinal seam creates stress concentration, v. local thinning in weld/heat-affected zones lowers t, vi. defects initiate early plastic instability.

Therefore, the true failure pressure may plausibly lie in the range of 50–70 bar. By comparison, certified industrial aluminium gas cylinders are normally hydrostatically tested at 1.5–2.0× their working pressure and are produced to strict weld-free seamless standards- unlike this fabricated vessel. Unrestrained hydrogen production inside a container system using reaction procedures such as aluminium + sodium hydroxide + water which can quickly reach and surpass this pressure range and leading to mechanical burst explosion. This is consistent with the ductile shell tearing and absence of soot or thermal charring. Therefore, the container having less safety precautions and was never appropriate for containing rapidly generated hydrogen.

The estimated pressure at cylinder would rupture in the range of 73 bar based on measured dimensions and conservative strength value. These values considered as very low compared to certified hydrogen cylinders and designed and tested for 150–200 bar with maximum thicker walls.

**Hydrogen pressure development inside the fabricated aluminium cylinder: Internal free Volume of the Cylinder:** The internal volume was approximately:

$$V = \pi r^2 L = \pi (0.0464)^2 (0.49) = 0.00331 m^3 = 3.31L$$

This value is used in the pressure estimation that follows.

**Pressure rise from Hydrogen accumulation:** Schematic representation of hydrogen gas generation inside a sealed aluminium cylinder due to contact between aluminium powder and moisture id shown in Figure-4. Assuming hydrogen behaves ideally, the pressure–volume relationship is governed by the ideal gas law[17]:

$$PV = nRT$$

The pressure is directly proportional to the number of moles of gas present at constant temperature and constant vessel volume.

If m grams of aluminium react, the moles of hydrogen produced are:

$$n_{H_2} = 1.5\left(\frac{m}{26.98}\right)$$

Substituting into the ideal-gas equation and rearranging gives:

$$P = \frac{1.5mRT}{26.98V}$$

To illustrate practically, consider only 5 g of aluminium reacting — a very small quantity compared with the mass typically present in precursor mixtures.

$$n_{H_2} = 1.5\left(\frac{5}{26.98}\right) = 0.278\,mol$$

At approximately 25 °C (298 K)**:**

$$P = \frac{(0.278)(8.314)(298)}{0.0035} = 196686\,Pa = 0.197\,Mpa = 1.94\,bar$$

So only 5 g of reacting aluminium already produces nearly 2 bar of internal pressure.

If 50 g of aluminium react — still a modest quantity:

$$P_{50g} = 10 \times 1.94 \approx 19\,bar$$

And if 100 g of aluminium react:

$$P_{100g} \approx 38\,bar$$

These pressures approach and exceed the probable failure range (≈ 50–70 bar) previously estimated for the fabricated aluminium cylinder. Because the chemical reaction remains active while unreacted aluminium persists and moisture is present, it is entirely feasible that pressure continues rising until structural burst occurs.

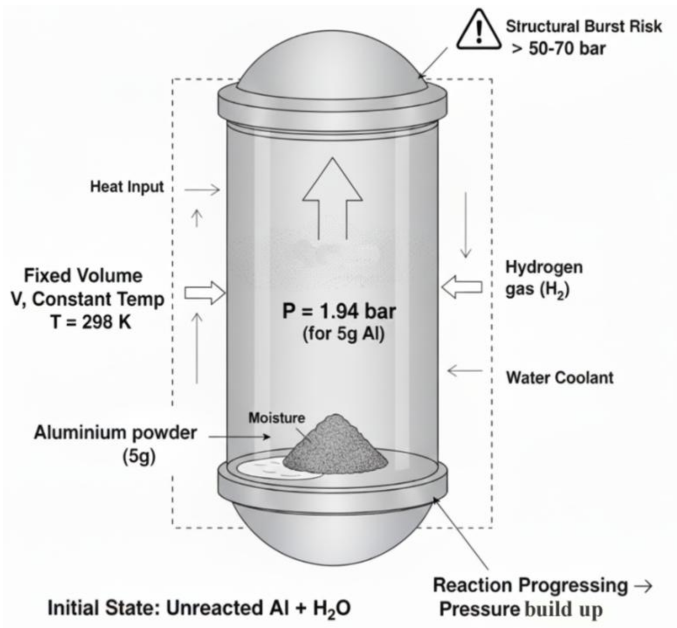


**Figure-4:** Schematic representation of hydrogen gas generation inside a sealed aluminium cylinder due to contact between aluminium powder and moisture.

**Interpretation in relation to cylinder failure:** The above calculations demonstrate that even tens of grams of aluminium reacting with sodium hydroxide and water can generate hydrogen in volumes many times greater than the internal capacity of the vessel. In a sealed container, this necessarily results in substantial pressure accumulation. When internal pressure reaches rupture stress threshold as calculated earlier the approximately 7.3 MPa ≈ 73 bar, at this point the cylindrical wall experiences critical hoop stress and sudden tearing failure. Such a mechanism is consistent with: i. Absence of soot or thermal burning, ii. Fragmentation rather than melting, iii. tearing features characteristic of ductile mechanical rupture, and iv. The presence of unreached precursor materials at the scene.

**Preventive Measures and Recommendations: Handling and Storage:** The present case describes the hazards that occur when reactive metals, alkalis and offhand pressure vessels are managed without proper technical assistance. Aluminium granules, caustic soda pellets, and water should not be stored or transported all together in improvised containers or less ventilated environment. Containers designed for reactive materials should be abide by engineering standards, be manufactured from certified materials, and, where feasible also avoid welded seams that may act as points of weakness. Special attention is given with aluminium due to sodium hydroxide can dissolve its protective oxide layer and exposing fresh metal surfaces which can lead to the rapid gas evolution.

**Law-Enforcement and Forensic Guidance:** In the place of incident we may find the unexplained fragments of metal containers, absence of soot deposition and presence of caustic residues should indicates the consideration of chemically driven hydrogen pressurization as a potential cause. So, recovery of intact pellets, powders, swabs, residues, and liquid phases is essential to collect for further examination and together with documentation of vessel geometry, weld condition, and fracture morphology.

It is very important to assess and interpret the mechanical evaluation of vessel strength and fracture behavior with better coordination between investigators and forensic laboratories.

## Conclusion

The present research article describes the considering the anonymised case study was examined as the structural integrity and failure potential of an aluminium cylinder recycled for the production and to store the hydrogen gas. Based on the physical parameters of the cylindrical container confirmed that the container having an external diameter of 98 mm and a wall thickness of 2.6 mm, ensuring in a diameter-to-thickness ratio of 37.7 as calculated and limiting threshold of 20 for thin-walled assumptions. This describes the theory of application of thin-wall pressure vessel for stress and estimation of burst-pressure.

The theoretical burst pressure estimation positioned with published values for comparable aluminium vessels, reinforcing confidence in the analytical method. However, the existence of longitudinal and circumferential welds seams in the container which introduces local stress concentration and metallurgical weakening, thereby reducing the effective burst margin. Moreover, semi-ellipsoidal domed ends present in the container modify stress distribution and increasing the hoop stress within the cylindrical container where rupture preferentially initiates.
From a forensic stand of point, when reconstructing accidental or intentional hydrogen-related explosions place very important role to measure deformation patterns, fracture morphology, and weld-associated imperfections provide diagnostic signs. The work summarize the inevitability of following strictly to standard designs for pressurized vessels and exibits that repurposing containers for hydrogen storage describes an extreme structural and public-safety hazard.

Overall, this work emphasize an essential message: hydrogen storage must only be initiated using certified vessels clearly designed for hydrogen service, adopting suitable material selection, wall-thickness design, weld quality assurance, and pressure-relief provisions.

**Limitations of the Study:** Instead of controlled experimental replication, the current investigation is focused on analytical reconstruction and post-incident forensic assessment. As a result, it is important to recognize a number of restrictions. First, because the precise alloy composition, heat treatment state, and manufacture history of the cylinder were unknown, the mechanical evaluation of burst pressure depends on idealized thin-wall pressure-vessel theory and assumed material properties for aluminum. The actual failure pressure may be greatly impacted by variations in residual stresses, weld quality, and material strength. Specifically, compared to parent metal, welded seams and heat-affected zones frequently show decreased mechanical strength, which may lead to rupture at pressures lower than theoretical estimations.

Second, ideal gas behavior and constant temperature circumstances are assumed in the computation of hydrogen pressure development. The aluminum–alkali reaction is actually exothermic, and both reaction kinetics and pressure evolution may be changed by localized heating, phase interactions, or insufficient mixing. Uncertainty was introduced into the calculated pressure levels due to the inability to exactly quantify the amount of reactive material present and the degree of conversion at the time of rupture.

Third, external measurements and geometric assumptions about the semi-ellipsoidal end caps were used to estimate the vessel's internal capacity. The actual internal capacity might have been impacted by manufacturing tolerances or any deformation that occurred before rupture. Furthermore, it was unable to completely rule out potential leakage routes or partial venting during the process.

Lastly, dependence on indirect inference from structural damage and theoretical calculations is required due to the lack of direct pressure measurements at the time of failure. Although a hydrogen-driven over-pressurization process is highly supported by the combined chemical and mechanical investigations, other contributing elements such pre-existing flaws, fatigue damage, or impact impacts cannot be totally ruled out.

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