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Research Paper

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Evaluation of Hypothetical Fire Exposure Duration & Time of Failure Scenario in a Horton LPG Sphere

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Abstract

In this paper, the duration to failure of the LPG Horton sphere under fire exposure is evaluated using the given thermal, material, and operating data, enabling estimation of time-to-failure and assessment of the risk of catastrophic events such as BLEVE explosions and fire escalation. The paper examines the design aspects of Horton spheres, including size, shape, construction material, and the effect of fire-induced heat on the vessel. It also reviews applicable safety standards and protective measures such as fire protection systems, thermal insulation, and safe separation distances. The findings indicate that proper design combined with effective fire protection and adherence to safety guidelines significantly reduces accident risks, thereby enhancing safety and protecting human life, property, and the environment in LPG storage.

Keyword: Jet Fire, Pool fire, BLEVE, fire Exposure, Time failure

Introduction

Liquefied Petroleum Gas (LPG) is stored in large spherical pressure vessels known as Horton spheres, which are widely used in the oil and gas industry because of their high structural strength, uniform stress distribution, and increased resistance to fluctuating pressure and temperature. LPG is a highly flammable substance and expands rapidly when heated, making its storage safety a critical requirement. Industrial environments contain several fire hazards, including flammable liquids, gases, combustible materials, and electrical ignition sources. Fire incidents can lead to serious consequences such as explosions, toxic releases, heavy property damage, and loss of life. One major hazard during LPG tank fires is flame impingement, which occurs when the flame directly comes in contact with the tank surface. This results in extremely high heat transfer, causing the steel wall to weaken, pressure inside the tank to rise, and potentially leading to BLEVE or complete structural failure. The consequences include:

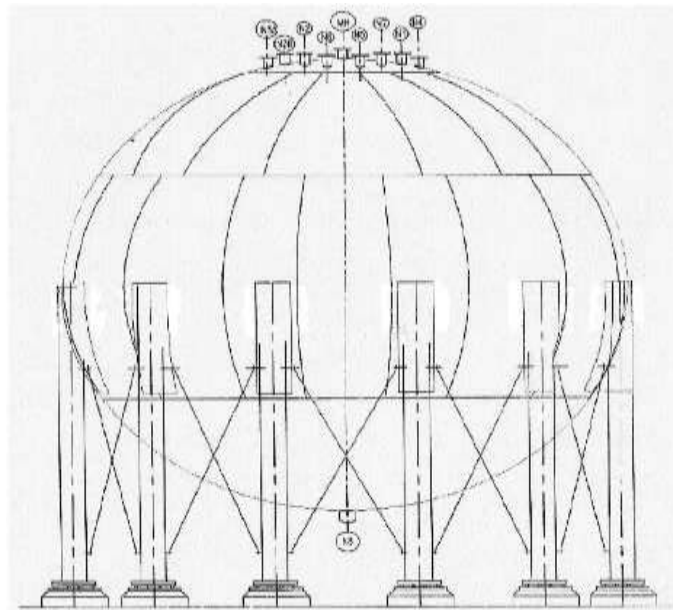
1. Equipment and infrastructure damage.
2. Severe injuries and fatalities.
3. High economic and environmental losses.
4. Community risk due to fire and vapour cloud explosion.

Therefore, evaluating the flame impingement effect on Horton spheres is essential to enhance fire protection, maintain structural integrity, and prevent major accidents. This study focuses on understanding heat transfer behaviour during flame contact, assessing thermal response of the tank wall, and improving fire safety standards.

Horton sphere

Whenever we talk about Horton spheres, these are custom-built as per ASME VIII, PD 5500, BS, and PESO codes. Diameters typically range from 10,000 mm to 22,000 mm or more, with shell thicknesses up to ~72 mm. Exact dimensions depend on the paper's specification.

Therefore, the data presented here represents typical vendor/manufacture design ranges for Horton spheres specific to LPG (Liquefied natural gas).



(LPG sphere Image – 1)



(LPG sphere Image – 2)

A. Technical Specification of a Typical LPG Sphere

Sr. No.	Parameter	Description / Value
1.	Tank Type	Horton Sphere (Spherical LPG Storage Tank)
2.	Orientation	Spherical, supported on legs at the equator
3.	Internal Diameter (Di)	18.00 m
4.	Shell Thickness	50 mm (Typical range: 20–72 mm)
5.	Outside Diameter (Do)	18.10 m
6.	Total Internal Volume	3,053.6 m ³
7.	Typical Liquid Fill	83%
8.	Liquid Volume	2,534.5 m ³

9.	Liquid Height from Bottom	13.28 m
10.	Design Pressure	21.2 kg/cm ² $\approx$ 2.079 MPa ($\approx$ 20.79 bar)
11.	Impingement Patch Size	Scenario-dependent (flame type, distance, modelling)
12.	Distance from Flame Source	Scenario-dependent (NFPA / API consequence analysis)
13.	Flame Elevation / Angle	Scenario-dependent (trajectory and flame modelling)

B. Material Basis – SA-537 Class 1 Carbon Steel

1.	Property	Value / Description
2.	Material Type	Carbon Steel – SA-537 Class 1
3.	Application	Pressure Vessel Steel for LPG Horton Spheres
4.	Density	$\sim 7,850 \text{ kg/m}^3$
5.	Specific Heat Capacity	0.49 J/g·K
6.	Thermal Conductivity	$\sim 50 \text{ W/m}\cdot\text{K}$
7.	Thermal Diffusivity	$\sim 1.0 \times 10^{-6} \text{ m}^2/\text{s}$
8.	Melting / Softening Temperature	$\sim 1450^\circ\text{C}$
9.	Critical Temperature	$T_{cr} = 593^\circ\text{C}$
10.	Critical Heat Flux	1000 kW/m ²
11.	Yield Strength at 20°C	$\sim 345 \text{ MPa}$
12.	Strength Retention	Adequate at normal LPG storage temperatures
13.	Thermal Expansion Coefficient	$\sim 11 \times 10^{-6} / ^\circ\text{C}$
14.	Young's Modulus	$\sim 200,000 \text{ MPa}$
15.	Maximum Allowable Working Pressure	Typically, up to 20 MPa (designdependent)
16.	Surface Condition	Normalized condition
17.	Protective Coating	Epoxy primer/paint (similar thermal response as bullet tanks)

Scenario 1: Fully Filled and Heated Sphere

- The tank is almost 100% filled with liquid LPG.
 - When heat from flame impingement is applied:
 - The liquid temperature increases rapidly. o Liquid expands but has no free space to accommodate expansion.
 - Pressure rises sharply.
 - Relief valves may not release sufficient vapour fast enough.
 - High pressure can exceed the design limit and lead to:
 - Rupture o BLEVE (Boiling Liquid Expanding Vapour Explosion)
- Filled tank = Highest explosion risk

Scenario 2: Partially Filled and Heated Sphere

- The tank has liquid + vapour space inside (common storage condition).
- When flame impingement occurs:

o The vapour space heats first. o Metal surface above liquid level becomes extremely hot. o Steel weakens due to high temperature.

o Eventually, the weakened metal collapses → tank rupture.

Partially filled tank = Highest structural failure risk because the upper shell is exposed directly to flame and becomes the weakest point.

3. Methodology

This Paper evaluates the effect of flame impingement on an LPG Horton sphere by calculating heat transfer to the tank wall, determining temperature rise, and assessing structural failure risk.

Fire Exposure Duration / Time to Failure

$$t_{fail} = \frac{(T_{cr} - T_0) \cdot \rho \cdot C_p \cdot t}{Q_{total}}$$

Where:

T_{cr} = Critical steel temperature

ρ = Density of steel

C_p = Specific heat capacity This gives time before the tank ruptures if no firefighting cooling occurs.

Given Hypothetical Data

Material: SA-537 Class 1 (Pressure vessel steel)

• Density, $\rho = 7850 \text{ kg/m}^3$

• Specific heat, $C_p = 0.49 \text{ kJ/kg} \cdot \text{K}$

• **Critical steel temperature** (fire case):

$T_{cr} = 593^\circ\text{C}$

• **Initial steel temperature:**

$T_0 = 30^\circ\text{C}$

Geometry & Fire Load □

Shell thickness:

$t = 0.03 \text{ m}$

• **Total heat flux (severe pool fire):**

$Q_{total} = 100 \text{ kW/m}^2$

Formula Used

$$t_{fail} = \frac{(T_{cr} - T_0) \rho C_p t}{Q_{total}}$$

Step-by-Step Calculation Step 1: Temperature rise

$T_{cr} - T_0 = 593 - 30 = 563 \text{ K}$

Step 2: Substitute values

$$t_{fail} = \frac{563 \times 7850 \times 0.49 \times 0.03}{100}$$

Step 3: Solve the numerator

$563 \times 7850 = 4,419,550$

$4,419,550 \times 0.49 = 2,165,580$ $2,165,580 \times 0.03 = 64,967$

Step 4: Result

$$t_{fail} = \frac{64,967}{100}$$

$t_{fail} \approx 650$ seconds

Final Answer

$t_{fail} \approx 650 \text{ s} \approx 10.8 \text{ minutes}$

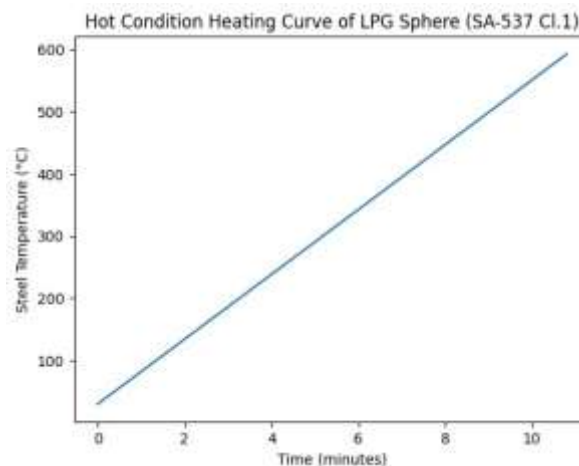
Why 593 °C is Used At around 590–600 °C:

- Yield strength drops to $\approx 20\text{--}30\%$ of the room-temperature value
- Creep deformation starts rapidly
- Internal LPG pressure causes plastic collapse
- Failure occurs even without a brittle fracture This temperature is widely used in:
- BLEVE analysis
- API / CCPS fire modelling ☐ LPG sphere fire safety calculations

3.6 Safety Mitigation Evaluation

After the calculation, evaluate the impacts of:

1. Passive Fire Protection (PFP coating)
2. Water spray cooling
3. Safe separation distance
4. Relief valve capacity



(Respective Time Temperature Graph)

Graph Explanation (Hot Condition – LPG Sphere) Graph Description

1. X-axis: Time (minutes)
2. Y-axis: Steel Temperature (°C)
3. Initial temperature: 30 °C
4. Critical steel temperature (hot CST): 593 °C
5. Failure time: 10.8 minutes

The graph shows a linear rise of steel temperature under constant fire heat flux, reaching the critical steel temperature at 10.8 minutes, which corresponds to structural failure / BLEVE risk.

Conclusion

Based on the thermal response analysis of an LPG sphere made of SA-537 Class 1 pressure vessel steel, the failure time under severe fire exposure was evaluated using a lumped heat capacity model. With a critical steel temperature of 593 °C, an initial temperature of 30 °C, a shell thickness of 0.03 m, and an incident heat flux of 100 kW/m², the calculated time to failure is approximately 650 seconds (≈ 10.8 minutes). The time–temperature graph

confirms a linear rise in steel temperature under constant heat flux, reaching the hot-condition critical steel temperature at 10.8 minutes. At this temperature, the steel experiences a significant loss of mechanical strength, making it incapable of safely containing internal LPG pressure and leading to a high risk of rupture or BLEVE. This study highlights that unprotected LPG spheres have very limited survival time in fire scenarios, emphasising the critical importance of water spray systems, thermal insulation, and effective emergency response measures to delay steel heating and prevent catastrophic failure.

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