Clean technology: Hydrogen safety guide

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Purpose and scope

This guide focuses on the safe handling of hydrogen and is developed for:

- Industry professionals involved in hydrogen projects
- Safety professionals and trainers
- Emergency responders.

The content highlights industry best practices, current standards and practical experience to provide guidance on hydrogen safety management.

For suggestions to improve the guide, please email contact_MHD@mom.gov.sg.

Published by Major Hazards Department (MHD)

Contents

1 Introduction

1.1 Importance of hydrogen safety

Hydrogen plays a vital role as a clean energy option, in the transition towards sustainable energy. Its unique physical properties require careful handling and comprehensive safety measures. This guide addresses fundamental aspects on hydrogen safety, including:

- Hydrogen’s properties and related hazards,
- Essential control measures,
- Applicable standards, and legal requirements
- Risk assessment strategies to ensure its safe utilisation across various applications.

The guide incorporates practical lessons learned from past hydrogen incidents and examines specific hazards related to different production methods, in particular electrolysis and syngas. By comparing against established hydrocarbon safety practices, the guide highlights key differences for hydrogen safety that require special considerations. Emphasis is placed on explosion protection strategies and the implementation of gas detection technologies.

Through understanding and applying these safety principles, this guide aims to equip professionals with basic safety guidelines, towards effective management of hydrogen-related risks for safe use across different applications.

1.2 Keeping current

The field of hydrogen technology is rapidly evolving. Users of these guidelines are encouraged to:

- Check for updates to this document and relevant standards on a periodic basis.
- Stay informed about new technological developments and safety research.
- Participate in industry forums and safety working groups.
- Contribute to the continual improvement of hydrogen safety practices.

2 Overview of hydrogen applications

2.1 Categories of hydrogen infrastructure

The purpose of hydrogen applications can broadly be categorised into the following:

- Production.

- Storage and transport.
- Use of hydrogen.

Some applications may involve all three categories.

2.2 Production

The production of hydrogen marks the beginning of the hydrogen value chain. Multiple production pathways exist, employing various processes and technologies. Common production methods include:

Natural gas or naphtha reformation, water or brine electrolysis, and methane pyrolysis represent established production routes. Additional processes include chemical dehydrogenation, hydrocarbon steam cracking, and hydrogen displacement from acids using metals. Emerging technologies focus on sustainable approaches such as biomass and waste gasification.

These diverse production methods reflect the evolving nature of hydrogen technology and its growing importance in the energy sector.

2.3 Storage, transportation and distribution

Hydrogen must be safely store and transported to users. Hydrogen's inherent physical properties, such as its low boiling point and low density under ambient conditions, affect the ability to safely store and transport hydrogen in economically significant quantities. Several proven methods have been used to address these challenges, such as handling hydrogen as a refrigerated liquid or as a pressurised gas, for transportation via land, sea, or pipelines.

There are other methods of storage and delivery. For example, utilising different physical mechanisms for hydrogen storage such as the use of common liquid fuels (ammonia, methanol and methylcyclohexane etc) to contain hydrogen. Another approach is the use of metal hydrides to avoid high pressure or low-temperature storage conditions. These different methods can provide specific benefits as well as unique challenges, depending on the application and operating conditions.

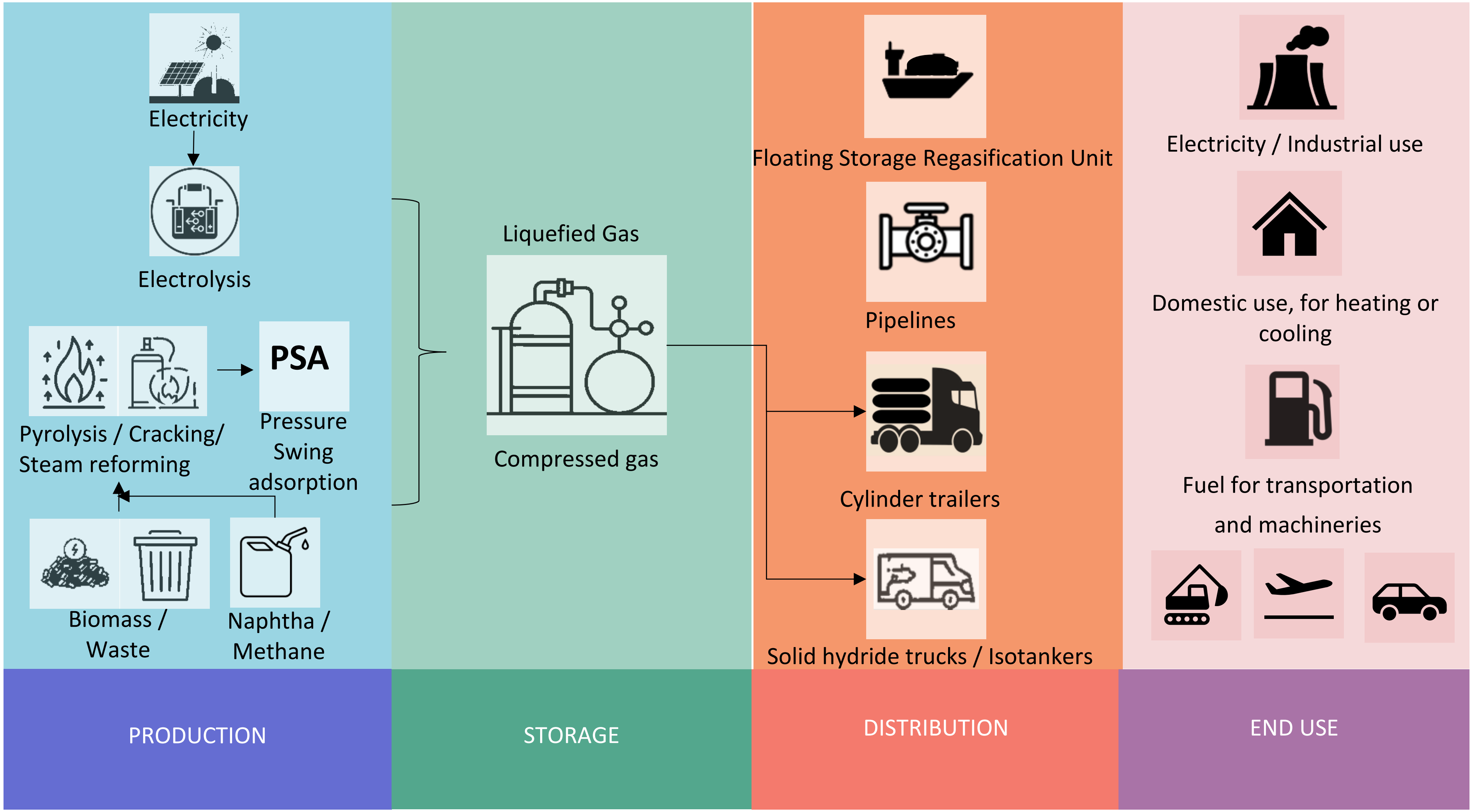
2.4 Use of hydrogen

Typical end-use applications of hydrogen include:

- Feedstock for industrial processes.
- Combustion fuel for industrial heating and process heat.

- Combustion fuel for domestic heating.
- Fuel for transportation and machineries.
- Production of electricity.

2.5 Hydrogen developments in Singapore



3 Legal requirements

3.1 Quantitative risk assessment (QRA)

QRA forms an essential part of safety management for hydrogen facilities in Singapore. Project developers should conduct a pre-consultation with the Major Hazards Department (MHD) to determine if their specific hydrogen project requires a QRA.

When required under the Environmental Protection and Management Act (EPMA) and Fire Safety Act (FSA), the QRA shall be conducted by approved QRA consultants and in adherence to the prevailing criteria. The QRA assesses potential hazard scenarios, their likelihood, and consequences, providing a comprehensive risk profile of the facility. Results of the QRA may inform critical safety design features, emergency response plans, and risk mitigation strategies.

Given the evolving nature of regulations in response to changing environments, project developers and facility operators should review and comply with the latest guidelines on QRA requirements for hydrogen facilities.

3.2 Regulatory requirements for hydrogen facilities in Singapore under the Workplace Safety and Health Act

Under the Workplace Safety and Health Act (WSHA), hydrogen facilities may be subject to specific regulatory requirements based on their operations and storage quantities:

3.2.1 Factory definition

A workplace handling hydrogen may be considered a factory under the WSH Act if it meets any one of the following criteria:

- Uses any form of power to move or work machinery for the purposes of processing materials.
- Processes or stores compressed hydrogen gas.
- Carries out industrial processes involving the use of hydrogen or other flammable gases.

3.2.2 Factory registration

A facility that manufactures syngas containing carbon monoxide shall register with the Commissioner for Workplace Safety and Health, as specified under Part 1 of the First Schedule under the Workplace Safety and Health (Registration of Factories) Regulations.

3.2.3 Major hazard installation registration

A facility storing or handling of hydrogen in quantities exceeding 25 tonnes shall register as a Major Hazard Installation (MHI). MHIs are required to develop and keep a Safety Case, toward the prevention of major accidents.

To register a factory or an MHI, refer to https://www.mom.gov.sg/workplace-safety-and-health/factory-notification-and-registration/requirements-for-factories

4 Properties and hazards of hydrogen

4.1 Hydrogen has several unique properties that contribute to its behaviour and potential hazards:

- **Lightweight**: Hydrogen is the lightest element, with a density of 0.08988 g/L at standard temperature and pressure.
- **Rapid diffusivity**: Hydrogen can quickly disperse in air and penetrate small openings due to its small molecular size.
- **Flammability and explosiveness**: Hydrogen has a wide flammability range of 4-75% in air, which is much wider than most other fuels.
- **Low ignition energy**: Hydrogen requires as low as 0.02 milli Joules to ignite. This is about ten times lower than that of traditional hydrocarbon gases.
- **Invisible flames**: Hydrogen burns with a nearly invisible flame, making fire detection and firefighting challenging.
- **Odourless and colourless**: In its pure form, hydrogen cannot be detected by human senses.

4.2 When working with hydrogen, it is essential to be aware of the following potential hazards:

4.2.1 Flammability and explosion risks

- Hydrogen's wide flammability range increases the risk of fire and explosion in the presence of any ignition source.
- The low ignition energy of hydrogen means that even small sparks or static electricity can trigger ignition.
- Rapid dispersion of hydrogen can lead to the formation of explosive mixtures in confined spaces.

4.2.2 Asphyxiation

- In high concentrations, hydrogen can displace oxygen in enclosed areas, potentially leading to asphyxiation.

4.2.3 Embrittlement

- Hydrogen can cause embrittlement in certain metals such as high strength ferritic and martensitic steels, leading to material degradation and potential failure of containment systems.

4.2.4 Cryogenic hazards

- Contact with liquid hydrogen stored at extremely low temperature (-253°C) can cause severe frostbite and damage to materials.

4.3 Additional hazards to consider for certain operations

4.3.1 Hazards specific to electrolysis for generation of hydrogen

Tip: Refer to Checklist for more info

- "Crossover Gas" phenomenon: Danger of forming flammable oxygen-hydrogen mixtures downstream, especially in electrolysis processes.
- Internal leakage: Cross leakage and air intrusion in hydrogen-containing equipment.
- Stack degradation: Degradation of stacks could happen due to chemical reactions, corrosion, and mechanical stress and may differ from stack to stack based on operating profiles.
- Electrical hazards: High voltage and current in electrolysis systems pose electrical shock risks.
- Chemical hazards: Use of corrosive electrolytes (e.g. alkaline solutions) can cause burns and equipment damage.
- Overpressurisation: Electrolysis systems can overpressurise if not properly controlled, leading to equipment failure.

4.3.2 Hazards specific to syngas production for generation of hydrogen

Tip: Refer to Checklist for more info

- Carbon monoxide (CO) Poisoning: Syngas typically contains significant amounts of CO, a highly toxic gas that can cause rapid asphyxiation.
- Fires and explosions from syngas components: Syngas also consists of methane, hydrogen, and other flammable gases that pose fire and explosion risks.
- High-temperature operation: Syngas production often involves high-temperature processes that can cause burns and equipment failure if not properly managed.
- Catalyst handling hazards: Catalysts used in syngas production processes can be hazardous if not handled correctly.

4.3.3 Hazards specific to pressure swing adsorption (PSA) for hydrogen purification

Tip: Refer to Checklist for more info

- High pressure operations: PSA systems operate at high pressures, which can pose risks of hydrogen leaks, ruptures, fire or explosions.
- Chemical hazards: The adsorbent materials used in PSA systems can be hazardous if not handled correctly. Exposure to these materials can pose health risks to workers.
- Thermal hazards: The adsorption and desorption processes can generate heat, which needs to be managed to prevent overheating and potential equipment failure.

5 Control measures

To mitigate the risks associated with hydrogen, the hierarchy of controls should be observed, and the following control measures should be implemented:

5.1 Containment and storage

- Design systems to safely contain the maximum expected pressure (inherently safe) or provide adequately sized pressure relief devices to protect against overpressure.
- Mount vessels and bottled gas cylinders securely.
- Protect storage areas against vehicle impact, accidental damage and unauthorised entry.
- Size storage appropriately for the service, avoiding too frequent deliveries or oversized systems.

5.2 Leak detection and mitigation

- Install hydrogen gas detectors and monitoring systems to promptly detect leaks or abnormal gas concentrations.
- Implement automatic shutdown and isolation systems if flammable mixtures are detected, particularly in enclosed spaces.
- Check for leaks in the operating system and perform maintenance regularly.

5.2.1 Sensor selection criteria:

- Ensure sensors can detect hydrogen at levels below the Lower Flammable Limit (LFL).
- Select sensors with fast response times to quickly detect and alarm on leaks.

- Consider parameters like temperature, humidity, and other environmental factors that can affect sensor performance.
- Evaluate maintenance needs and calibration frequency of different sensor technologies.

5.3 Ventilation

- Provide sufficient ventilation in areas where hydrogen is produced, stored, or used to prevent accumulation.
- Avoid build-up of hydrogen under ceilings, roofs, and other partly enclosed spaces.

5.4 Ignition source control

- Ensure proper bonding and grounding of equipment to prevent static electricity.
- Eliminate open and arcing/sparking devices in hydrogen-rich areas.
- Use appropriately classified electrical equipment in accordance with ATEX/IEC 60079 standards.
- Ensure appropriate administrative controls (e.g. hot work permit) are applied when working in areas storing or processing hydrogen.

5.4.1 Explosion protection (ATEX/IEC 60079)

- Conduct area classification studies to identify hazardous zones based on the frequency and duration of explosive atmospheres.
- Select equipment certified for use in the identified hazardous zones in accordance with ATEX/IEC 60079 standards (e.g., explosion-proof, intrinsically safe).
- Follow proper installation practices to maintain the integrity of explosion-protected equipment.
- Implement regular maintenance and inspection programs to ensure continued compliance with ATEX/IEC 60079 standards.

5.5 Emergency systems

- Install automatic fail-close tight shut shutoff valves at critical points in the system for isolation. Remote emergency shutdown should also be provided in facilities processing hydrogen.
- Implement warning systems with visible and audible signals to detect abnormal conditions.
- Develop and regularly practice emergency response procedures.

5.6 Material selection

- Use hydrogen-compatible materials to prevent embrittlement and ensure long-term integrity of systems by accounting for deterioration of mechanical properties during design.
- Select fire-resistant materials for construction and equipment in hydrogen areas.
- Eliminate the use of materials that exhibit low-temperature embrittlement (i.e., lack of toughness) for cryogenic services.

6 Risk assessment and ALARP principles

To ensure that risks are kept As Low As Reasonably Practicable (ALARP), a thorough risk assessment should be conducted:

6.1 Risk assessment methodologies

- HAZID (Hazard identification): Systematically identify potential hazards in the system.
- HAZOP (Hazard and operability study): Analyse process deviations and their consequences.
- QRA (Quantitative risk assessment): Evaluate the likelihood and consequences of potential incidents.
- FMEA (Failure modes and effects analysis): Assess potential failure modes at the component level.
- CFD (Computational fluid dynamics): Models gas dispersion, ventilation, and fire/explosion scenarios in hydrogen facilities for complex/ congested geometries.

6.2 Risk assessment process

- Identify potential hazards and scenarios related to hydrogen use in the specific application.
- Evaluate the likelihood and consequences of each identified hazard.
- Assess the effectiveness and independence of existing control measures.
- Determine if additional control measures are required to reduce risks to ALARP.
- Implement and monitor the effectiveness of control measures.
- Review and update the risk assessment.

6.3 ALARP considerations

- Consider industry best practices and emerging technologies for hydrogen safety.

- Ensure that residual risks are acceptable and justified.
- Proactively refine safety protocols by integrating new knowledge, operating experiences, and best practices.

7 Applicable standards (non-exhaustive)

I. General safety and system design

- ISO/TR 15916:2015: Basic considerations for the safety of hydrogen systems
- ANSI/AIAA G-095A-2017: Guide to safety of hydrogen and hydrogen Systems
- NASA: Safety Standard for hydrogen and hydrogen Systems: Guidelines for hydrogen system design, materials selection, operations, storage and transportation
- NFPA 2: Hydrogen Technologies Code

II. Explosive atmospheres and gas detection

- ISO 26142:2010: Hydrogen detection apparatus - Stationary applications

III. Production, storage, and distribution

a. Production and generation

- ISO 22734:2019: Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications

b. Storage and transportation

- ISO 16111:2018: Transportable gas storage devices - Hydrogen absorbed in reversible metal hydride
- CGA G-5.5: Hydrogen vent systems
- EIGA Doc 06/19: Safety in storage, handling and distribution of liquid hydrogen
- EIGA Doc 100/11: Hydrogen cylinders and transport vessels
- EIGA Doc 171/12: Storage of hydrogen in systems located underground

c. Piping and Pressure Vessels

- ASME B31.12: Hydrogen piping and pipelines
- EIGA Doc 121/14 / AIGA 033/14: Hydrogen pipeline systems

IV. Fuelling stations and vehicle refuelling

- ISO 19880-1:2020: Gaseous hydrogen - Fuelling stations - Part 1: General requirements
- EIGA Doc 15/06: Gaseous hydrogen stations
- ISO 17268:2020: Gaseous hydrogen land vehicle refuelling connection devices

V. Fuel cell technologies

- IEC 62282 series: Fuel cell technologies

VI. International standardisation efforts

- • ISO/TC 197: Hydrogen technologies

8 Other useful links

Facilities could also refer to the following links for more information around hydrogen safety:

Hydrogen tools portal by the Pacific Northwest National Laboratory

HIAD 2.1 Hydrogen incident and accidents database by European Commission

Checklist for facilities performing generation of hydrogen using electrolysis

- [ ] Was a QRA pre-consultation conducted to determine need for QRA?
- [ ] Was a QRA completed before construction and use?
- [ ] Were the quantities checked against MHI threshold and MHI registered if exceeded?
- [ ] Was a process hazard analysis conducted on the operations?
- [ ] Were past accidents pertaining to electrolysis of hydrogen gas studied and understood?
- [ ] Were the following hazards assessed:
    - Flammables and explosive risk (confinement)
    - Asphyxiation in enclosed area
    - Embrittlement of metals
    - Crossover Gas potential leading to flammable environment
    - Internal Leakage of air
    - Electrolyser Stack Degradation
    - Electrical Hazards, Cell polarity reversal, power surges, sudden shutdown
    - Chemical Hazards of corrosive electrolytes
    - Over pressurisation
- [ ] Was the facility designed to relevant standards?
- [ ] Were the following control measures considered:
    - Leak detection and mitigation systems
    - Ventilation
    - Ignition source control
    - Emergency response systems
    - Oxygen concentration monitoring and isolation systems
- [ ] Was a plan developed to collect operating data to support analysis of degradation mechanism?
- [ ] Were all necessary risk assessments including designs for safe maintenance completed to ensure risk is kept to ALARP?
- [ ] Was a pre-start up safety review completed before operating?
- [ ] Was a system implemented to record and investigate near misses and accidents?

Checklist for facilities performing generation of hydrogen using syngas and pressure swing adsorption

- [ ] Was a QRA pre-consultation conducted to determine need for QRA?
- [ ] Was a QRA completed before construction and use?
- [ ] Were the quantities checked against MHI threshold and MHI registered if exceeded?
- [ ] Was a Process Hazard Analysis conducted on the operations?
- [ ] Were past accidents pertaining to production of hydrogen gas studied and understood?
- [ ] Were the following hazards assessed:
    - Flammables and explosive risk (confinement)
    - Asphyxiation in enclosed area
    - Embrittlement of metals
    - Carbon monoxide hazards
    - High temperature hazards
    - High pressure hazards
    - Catalyst handling hazards
    - Chemical hazards
- [ ] Was the facility designed to relevant standards?
- [ ] Were the following control measures considered:
    - Leak detection and mitigation systems
    - Ventilation
    - Ignition source control
    - Emergency response systems
- [ ] Was a plan developed to collect operating data to support analysis of degradation mechanism?
- [ ] Were all necessary risk assessments including designs for safe maintenance completed to ensure risk is kept to ALARP?
- [ ] Was a pre-start up safety review completed before operating?
- [ ] Was a system implemented to record and investigate near misses and accidents?

Checklist for hydrogen refuelling station

- ☐ Was a QRA pre-consultation conducted to determine need for QRA?
- ☐ Was a QRA completed before construction and use?
- ☐ Were the quantities checked against MHI threshold and MHI registered if exceeded?
- ☐ Was a process hazard analysis conducted on the operations?
- ☐ Were past accidents pertaining to refuelling of hydrogen gas studied and understood?
- ☐ Were the following hazards assessed:
  - Flammables and explosive risk (confinement)
  - Asphyxiation in enclosed area
  - Embrittlement of metals
  - High pressure hazards
- ☐ Was the facility designed to relevant standards?
- ☐ Were the following control measures considered:
  - Leak detection and mitigation systems
  - Ventilation
  - Ignition source control
  - Training of personnel and human factors for refuelling stations
  - Emergency response systems
- ☐ Was a plan developed to collect operating data to support analysis of degradation mechanism?
- ☐ Were all necessary risk assessments including designs for safe maintenance completed to ensure risk is kept to ALARP?
- ☐ Was a pre-start up safety review completed before operating?
- ☐ Was a system implemented to record and investigate near misses and accidents?