Hydrogen Ballooning

May 2025 Minnesota Balloon Workshop

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Overview

- Why switch back to hydrogen
- Historic use and lessons learned
- Modern use approach
  - Hazard analysis and mitigations CONOPS
- Resources
  - Database
  - Literatures
  - Applicable organizations

NASA Project Timeline

Literature Review on Hydrogen Ballooning and best practices

Spread information through presentations and publications

Initiated International Hydrogen Balloon Working Group

Held in-person two-day meeting in May 2023 to discuss balloon operations

Meeting quarterly and discussions through email

Attended NASA Hydrogen Safety Training

Taught by WSTF Hydrogen team at Greenbelt, July 2023

Initiated BPO/WSTF Hydrogen Risk Analysis Team

Analysis of appropriate safety setbacks

Generation of complete hazard analysis with source data and mitigation options

Inflation testing

Develop CONOPS for various scenarios

Develop training plans

Begin operations

Why Use Hydrogen?

- Using hydrogen as a lift gas is not a novel concept. There are inherent risks that can be mitigated or reduced that make the use of hydrogen feasible. The lessons learned through historical use is invaluable.
- The cost of hydrogen is typically 5-10x less than helium and is readily available worldwide (it can even be generated in remote locations which greatly reduces the cost of transportation). This is the driving factor towards the change in lift gas.
- There will be an approximate 8% increase in available lift which will likely be offset for a need for additional ballast
  - [2] BT-3812. Flight Information, Flights S-66 thru S-82 Using Hydrogen, Vol. 1. Tufts College. Alvin Howell. 15JUL1953. Technical Report 3 Vol 1 Contract AF19(122)-63.
    - “thermal unbalances” or radiation unbalances which cause the balloon to ascend or descend separate from sunrise or sunset requires more ballast than for helium or ammonia
    - Hydrogen has a higher thermal conductivity, specific heat capacity, and thermal diffusivity than helium

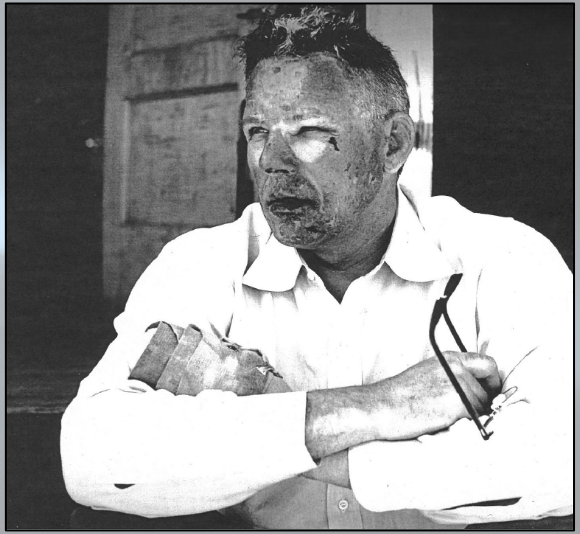
Hydrogen with Plastic Balloons

- Before 1940s, most balloons used hydrogen as the lifting gas. Helium was prohibitively expensive. Due to barrage balloon use in the wars, the US began to produce and stockpile helium as a matter of national priority.
- Since introduction of plastic balloons:
  - Over 2000 identified scientific balloon flights using hydrogen
  - Flights from 9 countries with 8 organizations
  - NSBF/CSBF last identified balloon launch using hydrogen was in 1982
- Once helium became cheap enough, most/all organizations moved to using it as a lift gas.
- In recent years, international partners sought return to hydrogen before NASA considered it

Notable Hydrogen Mishaps - Plastic Free Balloons

- **1955** – Air Force Research Lab, 3 personnel severely burned by molten polyethylene (shown is least injured).
- **1962** – UK, crewed balloon exploded and burned during deflation after pulling rip panel, injuries unknown.
- **Late 1970s** – Argentina Air Force, Balloon caught fire after launch. **No injuries.**
- **1976** – CNES, Auxiliary balloon burst and straps in flight train burned. **No injuries.**
- **1980** – CNES, Fire of inflation bench during test without balloon. **No injuries.**
- **1980** – CSBF, Leak in diffuser ignited when diffuser placed in inflation tube. **No injuries.**
- **1984**- CNES, Fire in inflation sleeve. **No injuries.**
- **1988** – CNES, Balloon caught fire after launch. **No injuries.**
- **1992** – CNES, Fire at top of balloon that had no valve but a metal plate with layer of foam. **No injuries.**
- **1999** – CNES, Balloon fire on launch pad after pause in launch operations. **No injuries.**
- **2017** – World View, Balloon caught fire during passive abort. **No injuries** but damage occurred to buildings due to overpressure.

Right: injured man from 1955 incident
Below: remains of balloon from 1955



Bottom: Worldview balloon deflagration

Note: US and CNES data was most readily available and the success rate during these periods was still >90%

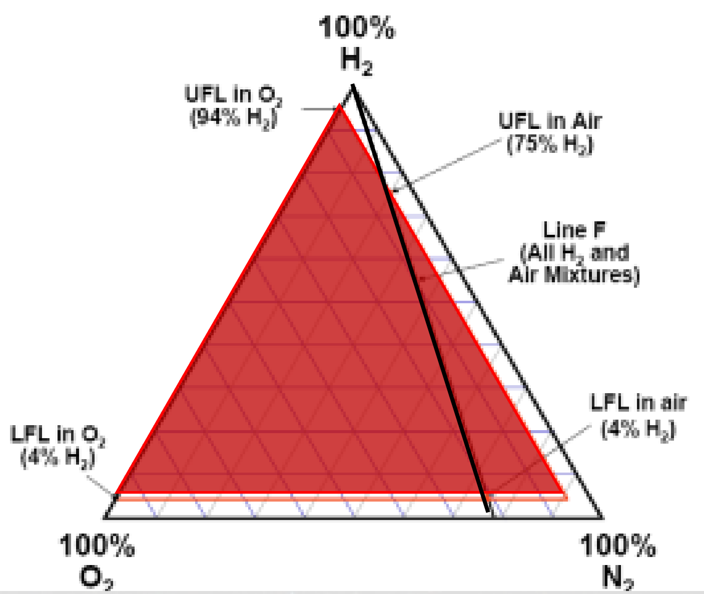
General Hazards

- High Pressure Risks
  - Same as those for helium, mitigated through strict operational and training controls
- Not toxic but can cause asphyxiation
  - Same as those for helium, mitigated by using in open air
- Hydrogen flame is not visible
  - If fire is suspected around fittings or in accessible area, a corn broom is effective for detection
- Hydrogen has a wide flammability range (4-75% in air) and ignition energy can be very low (17μJ)
  - Mitigation through strict electrostatic discharge control methods and line purging with pure nitrogen where feasible
- Flame and molten plastic from ignition/combustion event
  - Mitigated through flame-resistant, anti-static coveralls (with gloves and potentially face shields or hoods) in addition to currently required hard hats, steel toes, eye and ear protection
- Pressure wave from ignition/combustion event
  - Calculate proper stand-off distances, limit personnel inside the hazard area
  - Proper PPE for sound pressure levels and infrared exposure

These hazards are those that cause the most fear from personnel without an intimate knowledge of the specific details of hydrogen combustion events. The following slides work to broaden understanding of the mechanisms and mitigations.

Hydrogen Properties and Inherent Hazards

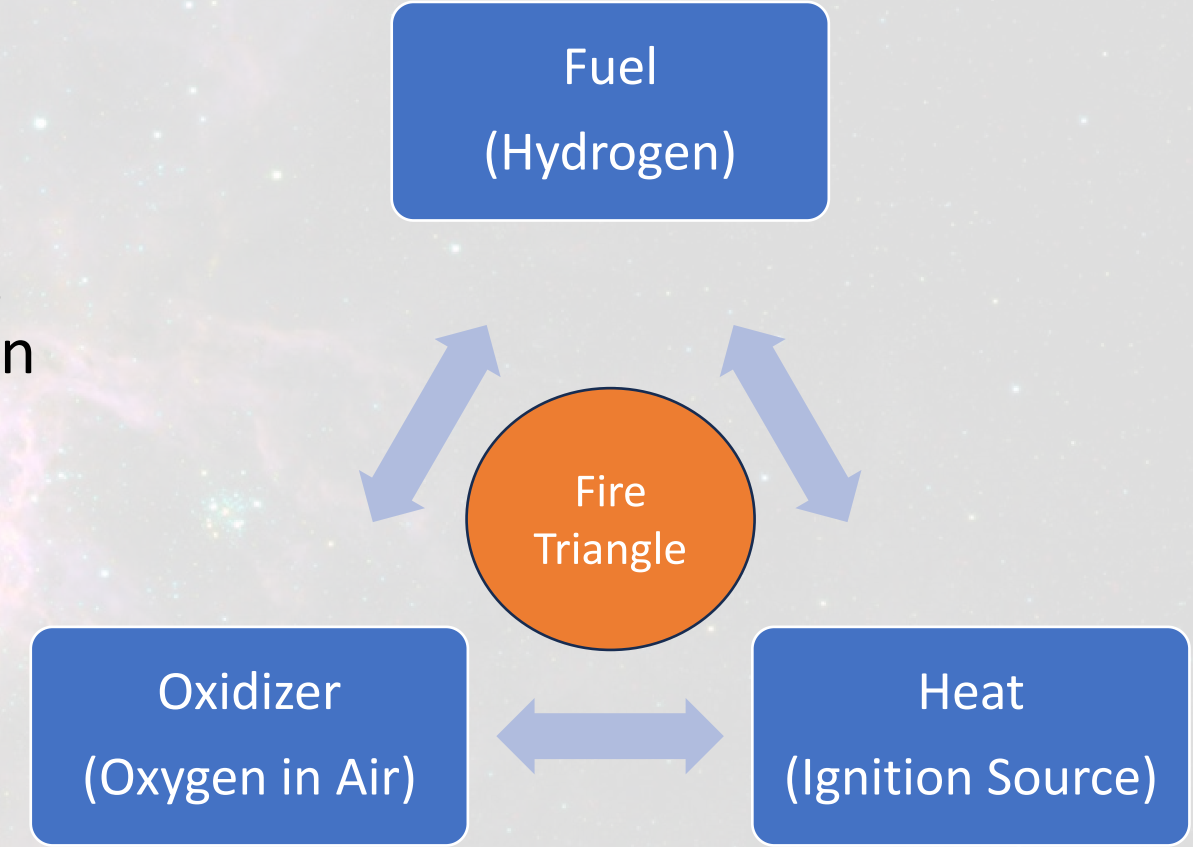
- Flammability Characteristics
  - Extremely flammable with wide flammability range (4-75% concentration in air) [5, 7]
    - Buoyancy slightly mitigates this hazard by driving the flammable gas mixture upward at a rapid pace
  - Minimal ignition energy required (0.02 mJ, 10x less than hydrocarbon gases) [5, 7]
  - Pure hydrogen exhibits more severe combustion behaviors than mixed concentrations:
    - Higher blast pressure and greater impulse
    - Larger flame size and more extensive damage potential [9]
- Physical Properties Creating Risks
  - Invisible flame and odorless gas complicates leak detection [5, 7]
  - Hydrogen embrittlement can affect metal components over time [18]
  - Potential for spontaneous ignition when rapidly released through small orifice [5, 7]
  - Convective and radiative heat transfer create hazards at varying distances [8]



Source: [16] Ring, Stott, and Hales, Modeling the Risk of Fire/Explosion due to Oxidizer/Fuel Leaks in the Ares 1 Interstage

Ignition/Combustion Events

- Fire triangle
  - ALL THREE COMPONENTS MUST BE PRESENT
- “Non-mass explosion, fragment producing”
- DoD 6055.09-M (Ammunition and Explosives Safety Standard). Per that standard, hydrogen is classified as Hazard Division 1.2 — “Non-mass explosion, fragment producing”
  - For each type of explosive, the hazards can be assessed in four categories: firebrands, fragments, blast, and thermal
  - For Division 1.2 hazards, the DoD standard states that **fragments** are the main hazard, with **firebrands** as the secondary hazards



$$H_2 + O_2 \longrightarrow 2H_2O + \text{Energy}$$

Hydrogen burns in two modes

Most likely scenario

- **Deflagration** – flame travels through mixture at subsonic speeds
  - This happens when an unconfined cloud of hydrogen-air mixture is ignited by a small ignition source
  - The flame will travel anywhere from ten to several hundred feet per sec.
  - The rapid expansion of hot gases will produce a pressure wave
  - Witnesses hear a noise (often loud) and feel a pressure wave that can damage nearby structures

Typically only from combustion in confined spaces

- **Detonation** – flame and shock wave travels together at supersonic speeds
  - Often build up from ordinary deflagration in a confined or partly-confined mixture (could happen inside the balloon or in folds, pockets of balloon)
  - It takes a POWERFUL ignition source to produce a detonation in an unconfined hydrogen-air mixture
  - Pressure ratio across a detonation wave is about 20. When the wave strikes an obstacle the wave is multiplied 2 to 3 times (so the ratio becomes 40 to 60)

Fire and Explosion Hazards

Per categories in DoD Ammunition and Explosives Safety Standard (DOD 6055.09-M)

Hydrogen: Classified as Hazard Division 1.2 – "Non-mass explosion, fragment producing"

Firebrands

"Hazard in the immediate vicinity"

Balloon material and brush/grass

Fragments

"The main hazard for HD 1.2, especially secondary fragments from containers and structures."

Valve and other components

Mitigation

- ***Use flame-retardant fabrics***
- ***No pilots in lighter-than-air vehicles***
- ***Maintain standoff distance***

- ***Vented enclosures***
- ***Fragmentation-resistant vessels***

Blast

"Effects limited to the immediate vicinity and are not considered to be a significant hazard."

Thermal

"Less thermal risk than HD 1.1 or HD 1.3. Progressive nature provides an opportunity for a fire suppression system."

Mitigation

- ***Maintain standoff distance***

Heat, sound, fire

- ***Operate outside***
- ***Implement fire suppression***
- ***Implement shut-off mechanisms***

Cable ladder, fittings that get hot from flames

This slide was reproduced with permission of the author and contain video of hydrogen fires

Gerald Knoblach, Chairman and CEO of Space Data Corp – AIAA Balloon Sys TC Member
Erik Limpaecher, Chief Innovation Officer & Team Lead – Hydrogen Production Systems for Mach Industries

The Hindenburg Disaster

Primary hazard was firebrands, not hydrogen

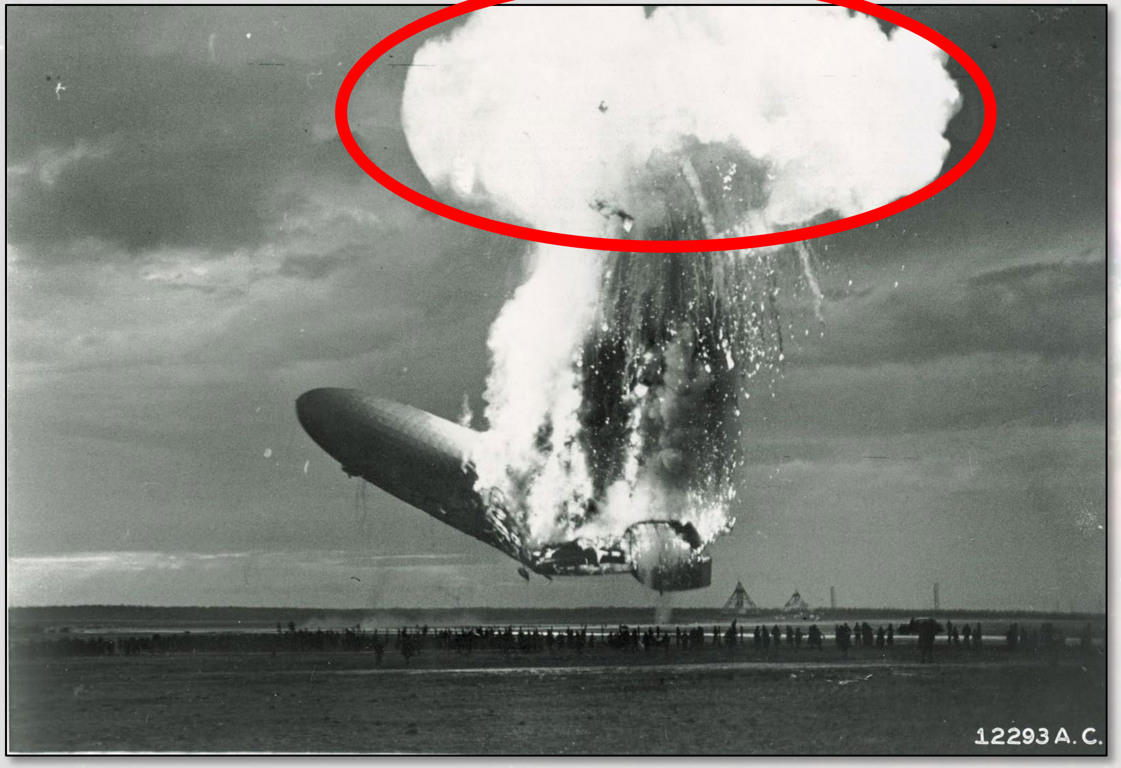

The New York Times

Hydrogen May Not Have Caused Hindenburg's Fiery End

By Malcolm W. Browne

"'The outer covering was much like sheets of Solid Rocket Motor grains.' … The dope-impregnated canvas skins of 1930's airships were chemically similar to the rocket fuel used by the space shuttle's solid boosters. …Even the metal girders of the Hindenburg's inner framework were coated with a highly flammable substance"

- Addison Bain, head of NASA's hydrogen program, in N.Y. Times, May 1997



Initial Hydrogen Explosion
(7 million cubic feet of H_2)

Subsequent Firebrand Hazard
(doped fabric and painted girders)

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Electrical Safety & Static Prevention

AI Overview

A typical static shock from shoes on carpet, often felt as a mild electric jolt, usually has a voltage between 2000 and 25,000 volts. The energy in a static shock is not typically high enough to cause harm, but it can be unpleasant. The energy of a static shock is related to both the voltage and the charge.

When pulling film from the roll NASA measured 100-300 V when we flailed and flapped it around and rubbed it the highest reading was around 2000 V with handheld ESD meter and no real controlled test conditions.

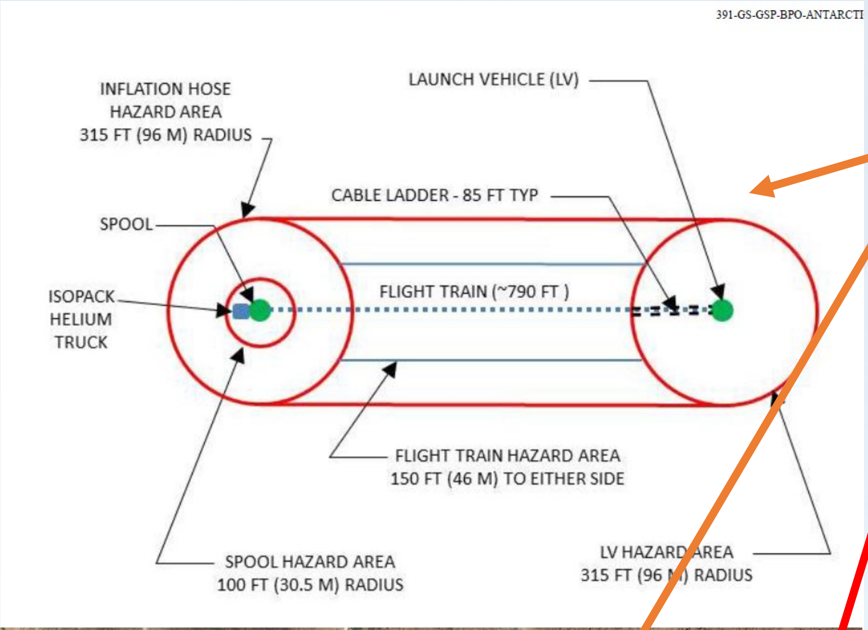
The minimum ignition energy (MIE) for a stoichiometric hydrogen-air mixture is very low, typically around 0.017 to 0.02 mJ. This translates to a spark voltage of roughly 2000 V. [22]

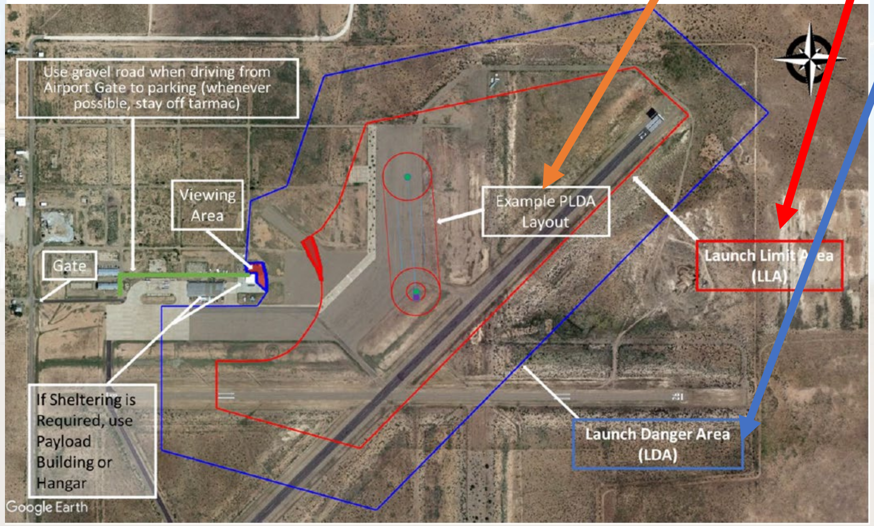
- Grounding Requirements
  - Maintain entire system at same electrical potential [1, 4, 14, 15]
  - Connect and verify grounding system before operations begin [4]
  - Ground both sides of connections before breaking them [4]
  - Incorporate grounding points throughout the inflation system [6]
- Static Electricity Management
  - Increase humidity to reduce electrostatic discharge risk [1, 12, 14]
  - Use conductive flooring in hydrogen operations areas [5, 7]
  - Apply detergent-water solution to plastic surfaces to increase conductivity [4, 6]
  - Consider design modifications to inflation system to reduce static generation [10]
- Personnel Static Protection
  - Wear anti-static clothing, leg static dissipators, and conductive footwear [1, 12, 14]
  - Use pure cotton or Nomex garments; avoid synthetic materials [1, 5, 7]
  - Require fire-resistant coveralls with hoods for complete protection [1, 19, 20]
  - Note increasing prevalence of synthetic blends in modern clothing necessitates careful selection [19]

Ignition Source Control

- Spark Prevention
  - Eliminate friction sparks (hard objects shearing upon contact) [5, 7]
  - Prevent impact sparks through tool drop-protection measures [5]
  - Control electrical equipment (use intrinsically safe devices) [5, 7]
  - Implement remote control of gas shut-off valves [10]
- Exclusion Zones
  - Historic 50-150 foot exclusion zone around hydrogen operations [5, 13]
    - New zones based on blast effects are needed
    - Various models are available but validation is needed through additional testing
    - Test data shows overpressure of approximately 1.8kPa at close range for 100% hydrogen balloon (1 m^3) [9]
      - Testing at scale that matches planned operations (+ 5000 m^3) is ideal but challenging [11] literature maxes out at 300 m^3
  - Prohibit smoking, flames, and hot objects near hydrogen [5, 3]
  - No welding or cutting operations near hydrogen storage or handling [5]
  - Respect safety distances during critical operations [10]
  - IR exposure decreases predictably with distance from combustion event [8]
  - IR exposure decay based on ground level distances provides guidance for minimum safe distances [8]

Current NASA Launch Exclusion Areas





- **Pre-Launch Danger Area** – Essentially a hazard area with a circle centered around the two big hazards – the spool/launch size and the mobile launch vehicle/hanging payload side with parallel leg lines along the flight train. These danger areas limit personnel to only those who are trained/properly attired. This danger area does not change no matter the wind conditions, launch site, etc. The circles are 96 m radius. (see diagram)
- **Launch Limit Area** – Essentially the limits of the driveable surface of the mobile launch vehicle. The vehicle will only travel when the balloon is released from the spool (and most likely, before the payload is released from the vehicle). This is highly dependent on launch site, surface conditions, etc.
- **Launch Danger Area** – A 152 m (500 ft) buffer around the launch limit area – matches the dimensions and shape of the launch limit area. This is required because if the vehicle stops at the end of the launch limit area, the still tethered balloon has change to impact items further out (due to wind, etc).
- **Launch Hazard Area** – This is to be sure that personnel are watched/managed away from the flight line but at altitudes before the balloon has been confirmed to have a healthy ascent. The launch hazard area is a circle at low winds (due to its variableness) and because a cone as winds increase. Within the launch hazard area, people are asked to move inside (shelter-in-place) (well, except in approved viewing areas) and roadblocks are set up for any roads within the hazard area to prevent traffic from coming in.

Wind Speed (knots)	Drift Distance (feet)	FOS	LHA Radius = (Drift Distance * FOS) + Buffer	LHA Shape
2	503	1.5	1355 ft / 0.22 nmi/0.25 mi / 0.41 km	360° about launch direction
6	1509	1.5	2864 ft / 0.47 nmi/0.54 mi / 0.87 km	±60° about launch direction
12	3018	1.5	5127 ft / 0.84 nmi/0.97 mi / 1.56 km	±45° about launch direction
16	4024	1.5	6636 ft / 1.09 nmi/1.25 mi / 2.02 km	±30° about launch direction
22	5524	1.5	8886 ft / 1.46 nmi/ 1.68 mi / 2.71 km	±15° about launch direction

NOTE: This data assumes an abort or termination of the balloon at the spool or the launch platform prior to the payload being released.

Operational Controls

- Pre-Operation Planning
  - Develop detailed procedures specific to operation scale [4, 10]
  - Calculate required hydrogen volume and prepare emergency response plan [4]
  - Train personnel thoroughly on procedures and emergency responses [10]
  - Layout site to maximize safety, considering prevailing winds and access routes [6]
- Equipment Design Considerations
  - Evaluate alternatives to traditional equipment components:
    - Modified inflation bench system to avoid gas containment
    - Two-gas approach: starting with helium to safely hold valve [10]
  - Incorporate or modify destruct cords and safety lines for emergency deflation [6]
- Monitoring and Detection
  - Utilize hydrogen gas detectors throughout operational area [5, 7]
  - Perform continuous inspection during inflation to check for leaks [4]
  - Monitor weather conditions, particularly wind speed and direction [4]
  - Use appropriate pressure gauges and flow meters to track inflation progress [6]
- Emergency Response
  - Establish clear evacuation procedures and assembly points [5, 7]
  - Train staff on appropriate fire response techniques [4, 5]
  - Document and analyze potential overpressure effects to determine safe setback distances [11]
  - Implement balloon destruct mechanisms for emergency situations [6]

Possible Operational Implementations

- Hardware and Process Improvements
  - Addition of control operations to test system tightness
  - Reinforcement of purge and drain operations
  - Implementation of leak detectors and fail-safe valves
  - Modification of the valve on balloon envelope top (and other electronics)
  - Consideration of hybrid gas approach (helium start, hydrogen finish) [10]
  - Redesign systems for automation, remove humans from the hazard area
  - Strict ESD controls
- Material Selection
  - Ground cloths to protect balloon from surface irregularities [6]
  - Appropriate inflation tubes with consideration for static and operational needs
  - Proper selection of diffusers and inflation equipment [6, 21]
  - Review of all materials for static generation properties [1, 7, 14]
  - Hydrogen-safe (non-embrittled materials)
  - Proper PPE selection

Management and Sustainability

- Key Safety Factors
  - Thorough training of operational team members
  - Maintenance of safety measures and equipment
  - Strict adherence to established procedures
    - NASA values safety highly and BPO and CSBF both have internal and external safety personnel that push for continuing education and monitoring of processes
  - Careful analysis of any proposed changes [10]
- Long-Term Considerations
  - Implement appropriate management supervision for hydrogen operations
  - Analyze all modifications before implementation to verify safety is maintained
  - Ensure sustainability of safety culture and knowledge transfer [10]
  - Document lessons learned from tests and operations [6, 21]

Is It Worth The Risk?

- Given costs for mitigations and the need to still use helium we could see a 50% cost savings for lift gas for a domestic campaign
- Risks can be mitigated but not eliminated, however numerous changes to technologies reduces risk significantly!
    - Apply the three axioms for hydrogen safety [5]: adequate ventilation, leak prevention, elimination of ignition sources
    - In addition, implement: proper PPE, leak detection and fire detection, safety procedures
    - At least two barriers or safeguards SHALL be provided to prevent a given failure from mushrooming into a disaster. For instance: one safeguard against spillage might be a leak detector which automatically shuts off the flow; a second might be a shield to protect other equipment and a safe shelter for personnel
- In all of the incidents noted earlier with plastic balloons, to date, only one of them had injuries and it was largely due to laxness around proper use of PPE.
- Industry has pushed for new uses for hydrogen since 1999 such as fuel cells in cars, etc. The industry/infrastructure to support hydrogen use is more robust and the safety procedures required have improved as well.

Ongoing Barriers / Next Steps

- Modifying public perception
- Process changes add complexity which may increase launch time and reduce launch attempts
- There are still several unknown unknowns in this process which will take testing, research and implementation to discover
- Ignition tests with volumes larger or equal to current operations to verify which models are best for calculating appropriate exclusion zones (also called set-back distances and hazard areas)
- Developing detailed CONOPS for nominal launch and various launch abort scenarios
- Publication of the detailed hazard analysis and approval by all parties

Hydrogen Working Group Members

- International Working Group
  - Includes international space agencies: JAXA, SSC, CNES (Centre National d'Études Spatiales)
  - Includes domestic partners: Aerostar, NSC (Near Space Corporation), World View, Air Force Materiel Command, Sandia National Laboratories

Presentation References

1. Kubara, Robert. Safe Handling Procedures for Gaseous Hydrogen. National Scientific Balloon Facility. 1976. Technical.

2. BT-3812. Flight Information, Flights S-66 thru S-82 Using Hydrogen, Vol. 1. Tufts College. Alvin Howell. 15JUL1953. Technical Report 3 Vol 1 Contract AF19(122)-63.

3. Ordin, Paul M. Review of Hydrogen Accidents and Incidents in NASA Operations. National Aeronautics and Space Administration. Cleveland, OH : NASA Lewis Research Center, 1974. Technical Memorandum.

4. Stefan, Karl. Plan for Liquid Hydrogen Exercise. National Center for Atmospheric Research. 1970. Technical.

5. Advisory Panel on Experimental Fluids and Gases. Hydrogen Safety Manual. NASA Lewis Research Center. Washington, DC : National Aeronautics and Space Administration, 1968. [AIAA-G095A Guide to Safety of Hydrogen and Hydrogen Systems was published in 2017 and is the most recent update to this original manual]

6. Internal memo, not for release

7. Office of Safety and Mission Assurance. Safety Standard for Hydrogen and Hydrogen Systems: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation. National Aeronautics and Space Administration. Washington, DC : Office of Safety and Mission Assurance, 1997.

8. Ignition of Hydrogen Fuel in Large-Scale Balloons due to Electrostatic Discharge and Potential Mitigation Strategies v2.5, Report, Bangham Engineering, Inc. 12JUNE2018

9. Katsumi, T. Ignition tests of Hydrogen Balloon, presentation to Hydrogen Working Group April 17, 2025,

10. Jacqueline Gary, Bernard Dellery, Gerard Letrenne, Stephanie Venel and Andre Vargas. "Returning to Hydrogen Gas : a Strategic Decision to Continue Achievement of Stratospheric Balloons Flights," AIAA 2015-2911. AIAA Balloon Systems Conference. June 2015.

11. Woods, Stephan. Vapor Cloud Explosion Overpressure Evaluation. Preliminary Report. *Not Yet Available For Release.* NASA WSTF and WFF. 2025.

12. Zito, Ralph, Peterson, Wm C and Stanley, Kleinman. Meteorological Balloon Accident Study. New York University. s.l. : Signal Corps Engineering Labs, est 1952. Technical.

13. BT-2134 Raven Industries, Contract 834-PNW-69. Hydrogen as a Lifting Gas for Heavy Load Balloons. 1969.

14. Pritchard, C.L. and Beemer, J.D. Hydrogen as a Lifting Gas for Heavy Load Balloons. Forest Engineering Research. s.l. : Raven Industries, Inc, 1969.

15. Overs, Donald E. Flammable Balloon Gases, The Concerns, Experiences, Characteristics. 1980.

16. Ring, Stott, and Hales, Modeling the Risk of Fire/Explosion due to Oxidizer/Fuel Leaks in the Ares 1 Interstage

17. Independent Incident Review Team. World View Incident Investigation Report. s.l. : Pima County, Arizona, 2018.

18. Lee, Jonathan A. Hydrogen Embrittlement. National Aeronautics and Space Administration. Huntsville, Alabama : NASA Marshall Space Flight Center, 2016. Technical.

19. Howell, Alvin. Flight Information, Flights S-207 to -216; Project Equipment and Balloon Experience with Vernalis, CA. Air Force Cambridge Research Center, Tufts University. s.l. : Tufts University Project 119L, 1956.

20. Murray, William D. High Winds Project "Moby Dick". Air Force Cambridge Research Center, New York University. 1951.

21. Stefan, Karl. Liquid Hydrogen Exercise at Palestine. National Center for Atmospheric Research. 1970. p. 25, Technical.

22. Ryo Ono, Masaharu Nifuku, Shuzo Fujiwara, Sadashige Horiguchi, Tetsuji Oda, Minimum ignition energy of hydrogen–air mixture: Effects of humidity and spark duration, Journal of Electrostatics, Volume 65, Issue 2, 2007, Pages 87-93, https://doi.org/10.1016/j.elstat.2006.07.004. AND https://hyresponder.eu/wp-content/uploads/2021/06/Lecture-8-slides.pdf

Hydrogen Safety Global Organizations 1/2

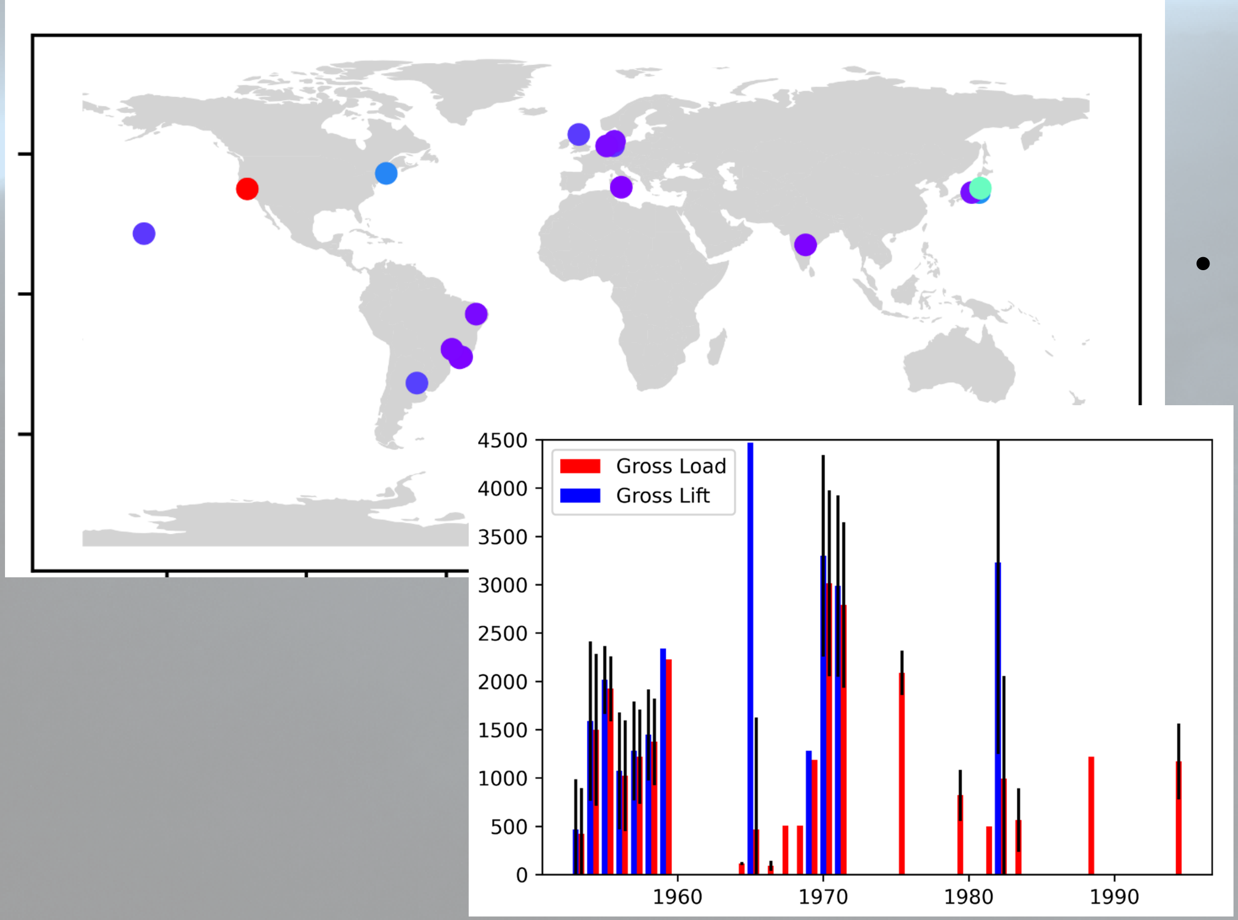
- United States
  - Department of Transportation (DOT): Regulates the transportation of hazardous materials, including hydrogen, via road, rail, and air through its Pipeline and Hazardous Materials Safety Administration (PHMSA).
  - Occupational Safety and Health Administration (OSHA): Ensures safe working conditions which include the storage and handling of hazardous gases like hydrogen.
  - National Institute of Standards and Technology (NIST): Provides guidelines on safety standards for hydrogen.
  - Department of Energy (DOE): Through the Hydrogen and Fuel Cell Technologies Office, the DOE conducts research and provides guidelines on hydrogen safety.
    - Hydrogen and Fuel Cell Safety (HFCS) Website - A resource provided by the DOE's Hydrogen and Fuel Cell Technologies Office, offering information on safety, codes, and standards relevant to hydrogen technologies.
  - Center for Hydrogen Safety (CHS): An initiative of the American Institute of Chemical Engineers (AIChE) dedicated to promoting hydrogen safety and supporting the safe development, handling, and use of hydrogen across various industries. Provides resources, training, and best practices for hydrogen safety and engages with the global hydrogen community to enhance safety protocols and standards.
  - National Fire Protection Association (NFPA) - - An international nonprofit organization focused on eliminating death, injury, property loss, and economic loss due to fire, electrical, and related hazards. Develops and publishes codes and standards for fire safety, including those relevant to hydrogen.
    - NFPA 2: Hydrogen Technologies Code provides comprehensive requirements for the design, installation, and operation of hydrogen systems to minimize fire and explosion hazards.
    - NFPA 55: Compressed Gases and Cryogenic Fluids Code includes guidelines for the storage, use, and handling of compressed gases, with specific sections addressing hydrogen safety.
- European Union
  - European Union Agency for the Cooperation of Energy Regulators (ACER): Ensures the application of EU energy regulations which include hydrogen as an emerging energy carrier.
  - European Union Regulation on the Classification, Labelling and Packaging (CLP): Part of REACH, this regulation ensures the safe handling and labeling of hazardous materials including hydrogen.
  - European Hydrogen Safety Panel (EHSP): Part of the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), focuses on hydrogen safety and provides recommendations for safety measures and practices.
  - Hydrogen Europe: A representative body of the hydrogen and fuel cell sector in Europe which also focuses on safety aspects.

Hydrogen Safety Global Organizations 2/2

- International Agencies
  - International Organization for Standardization (ISO): Develops and publishes international standards, including those related to the safe handling and transportation of hydrogen (e.g., ISO/TR 15916:2004 Basic considerations for the safety of hydrogen systems).
  - International Energy Agency (IEA): Works on global energy policies and includes a focus on hydrogen as part of future sustainable energy solutions.
  - United Nations Economic Commission for Europe (UNECE): Through the Global Forum for Road Traffic Safety (WP.1) and Inland Transport Committee, it develops international regulations that include transport of hazardous materials like hydrogen.
  - International Association for Hydrogen Safety (HySafe): Works on advancing hydrogen safety by promoting and co3ating research and development. Collaborates internationally to develop guidelines and best practices for safe hydrogen applications.
- Japan
  - Ministry of Economy, Trade and Industry (METI): Oversees hydrogen safety through its Agency for Natural Resources and Energy and ensures safety standards for the hydrogen economy.
  - High Pressure Gas Safety Institute of Japan (KHK): Provides safety regulations and certifications for the use and handling of high-pressure gases including hydrogen.
- Australia
  - Department of Industry, Science, Energy and Resources (DISER): Oversees hydrogen policies and safety regulations.
  - Standards Australia: Develops standards that include guidelines for hydrogen safety.
- Canada
  - Canadian Standards Association (CSA Group): Develops safety standards for hydrogen technologies and systems.
  - Natural Resources Canada (NRCan): Focuses on hydrogen as part of the country's energy strategy and includes safety considerations.
  - Canadian Hydrogen and Fuel Cell Association (CHFCA): Provides guidelines and standards for hydrogen safety in Canada and promotes safe practices within the industry.

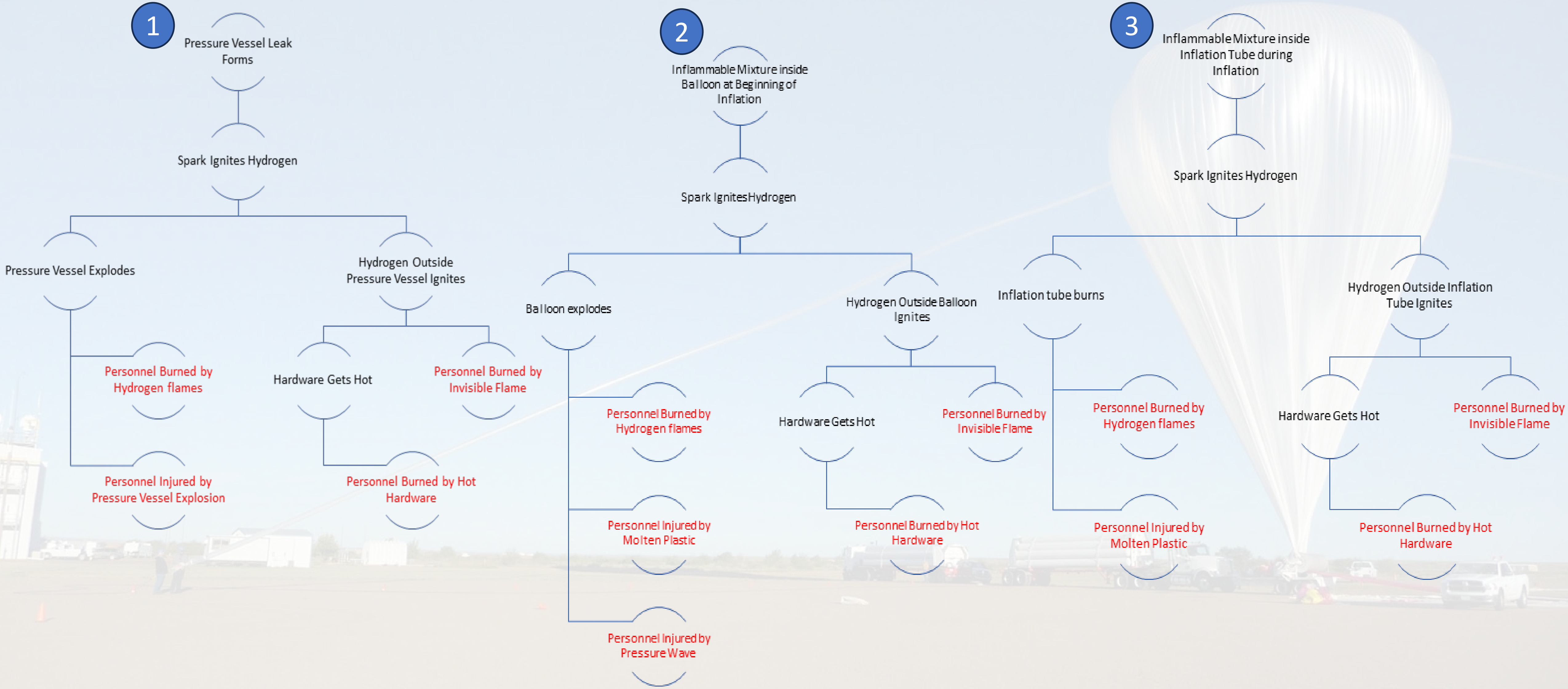
Hydrogen Database Flights

This database lists hydrogen balloon flights for plastic free balloons including an indicator for success or anomaly and notations of any injuries.



- Sources:
  - Balloon Technology Library -
    - Moby Dick flight records
    - Japanese conference reports
    - NCAR flight records,
  - Personal communication
  - Les Ballons Au Service De La Recherche
  - Stratocat – only when documented with primary sources
- Gaps
  - We know there are thousands of flights with hydrogen – only have full/partial source material for ~700 of these flights
  - Flight records from CNES, Japan, TFIR – it's not comprehensive for dates, flight times, balloon and payload sizes, material, etc
  - Also would like to get any reports on lessons learned, anomalies with regards to hydrogen
  - If you would like to contribute, please reach out to Erin Reed or Sarah Roth

Fault Tree Hazard Analysis 1/2



Fault Tree Hazard Analysis 2/2