Boeing Research & Technology

Quantifying the Hazards of Onboard Hydrogen Relative to Aviation Kerosene

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Boeing Research and Technology

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Abstract

In this presentation, we will analyze the prospect of hydrogen as an aviation fuel from the perspective of onboard ignition- and combustion-safety. Hydrogen is a zero-emission fuel that is receiving substantial investment. As a prospective replacement to jet fuel, hydrogen is a combination of benefits and detriments. Hydrogen boasts nearly three times the energy density as aviation kerosene by weight, but suffers from a significantly reduced volumetric energy density and is associated with aviation disasters—85 years later, many still connect hydrogen with the crash of the Hindenburg. Although the propensity for hydrogen to ignite has motivated many to conclude it is more dangerous than jet fuel, we will demonstrate that the entire picture is more nuanced with hydrogen being in fact safer than aviation kerosene in some aspects and more hazardous in others.

A major part of this analysis focuses on how current regulatory allowables—for example the ignitability of a kerosene-air environment such as described in FAA Advisory Circulatory 25.981—will change if the fuel under consideration is hydrogen. The analysis is bolstered by hydrogen-specific investigations to provide a framework to assess the hazard of hydrogen relative to aviation kerosene. Key metrics that are examined are flammability, ignitability, detectability, storability, flame heat flux, and detonability. Although the hazards of hydrogen should not be ignored, this analysis demonstrates that hydrogen is less hazardous than jet fuel in several key characteristics and the overall ignition-threat of hydrogen can be mitigated with appropriate design choices.

Multiple aerospace manufacturers are working towards hydrogen-powered flight demonstration vehicles with planned flights set to occur over the next decade. Hydrogen's unique properties imply that transitioning from a demonstration vehicle to a production vehicle will require a radically different ignition-safety strategy than is used in kerosene-based platforms in order to achieve equivalent performance and safety. In the next one to two decades, industry standards will be written that dictate the commercial use of hydrogen. The results of the safety analysis are used to propose best practices, and propose a fire and flammability mitigation strategy to accommodate hydrogen on commercial aircraft.

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Motivation – H_2 Case Studies

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Current proposals in Hydrogen Combustion Safety

- Brewer et al. (1977-1980)***:***

  The usual precautions *taken to minimize fire and explosion hazards in hydrocarbon fueled systems, such as separation of combustibles from ignition sources, compartmentization, compartment draining and purging must also be observed in the LH_2 airplane.*[1]

- SAE Aerospace Information Report (2019):

  Under normal operation, ***the risk of fire on hydrogen-based systems is lower than on kerosene-based ones****. This is because with hydrogen, ignition sources are not of concern as there is naturally no oxygen present within the system, while with kerosene, both oxygen presence and ignition sources have to be prevented through means that are subjected to failures. Lower risk can also be attributed to fewer and more concentrated tanks than in kerosene systems.*[2]

[1]: G.D. Brewer, R.E. Morris, G.W. Davis, E.F. Versaw, G.R. Cunnington, Jr., J.C. Riple, C.F. Baerst, G. Garmong. Study of Fuel Systems for LH2-Fueled Subsonic Transport Aircraft. Prepared under Contract NAS 1-14614 for NASA by Lockheed. NASA CR-145369. 1977 (volume 1) and 1978 (volume 2).
[2]: SAE Technical Report. Considerations for Hydrogen Fuel Cells in Airborne Applications. AIR7765. Issued Nov 2019.

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Air Mobility Command's Hydrogen Future: Sustainable Air Mobility[3]

- The Air Force sponsored a comparison of the safety of Hydrogen and JP-8 in 8 areas—see summary table to right.
- This study highlights misconceptions existing regarding hydrogen:
  - The key conclusion of "Detonability" is incorrect and has promulgated through multiple sources
  - The conclusion reached for "Fuel Spills" is technically correct, but misses the explosion risk that fuel spills create
  - The conclusions regarding "Invisible Flame" are only partially correct and should not be considered as impactful as the other safety considerations present

Reiman[3] Conclusions

Item	Advantage
Detonation	Hydrogen
Emissivity	Hydrogen
Frost Bite	JP-8
Fuel Spills	Hydrogen
Ignition Temperature	JP-8
Invisible Flame	JP-8
Suffocation	JP-8
Toxicity	Hydrogen

[3]: A.D. Reiman. AMC's Hydrogen Future: Sustainable Air Mobility. Master's Thesis. AFIT/IMO/ENS/09-13. 2009.

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Combustion Rules & Regulations – The Existing Approach

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FAA Advisory Circulatory – 25.981 Fuel Tank Ignition Source Prevention

- “Due to the difficulty in predicting fuel tank flammability and eliminating flammable vapors from the fuel tank, the regulatory authorities have always assumed that a flammable fuel/air mixture may exist in airplane fuel tanks and have required that no ignition sources be present.” [25.981-1D § 7.1.1]
- Assumes flammable environment exists, and mandates designs that prevent that environment from igniting

25.981 Requirements

Ignition Type	Jet-A	Hydrogen
Electrical Arcs	240 µJ actual * Requirement: 200 µJ	19 µJ actual [4] **Proposed Requirement: 15 µJ**
Filament Heating	Maximum currents: • Intrinsically safe: 25 mA • Steady-state failure: 50 mA • Transient failure: 125 mA	Unknown
Friction Sparks	Implementation of fail-safe features to mitigate	Unknown
Maximum Allowable Surface Temperature	430-450°F actual Requirement: 400°F	1085°F actual **Similar Level of Safety: 1035°F**

***** >200 µJ is the historically accepted Minimum Ignition Energy (MIE) of a theoretical worst-case Jet-A ullage; referenced data on light hydrocarbon ignition has an MIE of $2.4 \cdot 10^{-4}$ J.

[4]: H.F. Calcote, C.A. Gregory, Jr., C.M. Barnett, R.B. Gilmer. Spark Ignition: Effect of Molecular Structure. Ind and Engr Chem, 44(11). 1952.

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FAA Advisory Circulatory – 25.981 Fuel Tank Ignition Source Prevention Extended

- Additional ignition requirements should be added to 25.981 owing to the differences between hydrogen and jet fuel
- These new requirements would be applicable to environments that could contain hydrogen and air

Expected New Ignition Requirements

Ignition Type	Hydrogen
Shock Protection	Hydrogen-Air is shock sensitive: • Slow-acting valves • Crash protection
Allowable Vent Rates	Rapidly released hydrogen has been linked to spontaneous combustion: • Approved emergency hydrogen evacuation procedure • Evaluate hydrogen bleed-off
Exterior Ignition Sources	Vented hydrogen will create a relatively large cloud of ignitable gas exterior to the aircraft: • Flammable zoning outside aircraft may become important

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FAA Advisory Circulatory – 25.975 Fuel Vent Fire Protection

- AC 25.975 provides information and guidance to demonstrate compliance with the airworthiness standards for flame arrestors.
  - Flame arrestors are engineering features that are currently in place to allow the safe venting of fuel without an external ignition source propagating back through the vent.

- The increased flammability of hydrogen would require significant redesign of flame arrestors
  - At minimum, the diameter of the individual vent paths would need to decrease by a factor of ~13
  - Brewer et al. [1] posit flame arrestors would not be functional on a hydrogen-fueled aircraft.

[1]: G.D. Brewer, R.E. Morris, G.W. Davis, E.F. Versaw, G.R. Cunnington, Jr., J.C. Riple, C.F. Baerst, G. Garmong. Study of Fuel Systems for LH2-Fueled Subsonic Transport Aircraft. Prepared under Contract NAS 1-14614 for NASA by Lockheed. NASA CR-145369. 1977 (volume 1) and 1978 (volume 2).

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H_2 Combustion Safety: A New Approach

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H_2 Combustion Safety: A New Approach

Consider six factors in assessing the ignition threat of hydrogen:

1. Flammability
2. Ignitability
3. Detectability
4. Storability
5. Flame Heat Flux
6. Detonability

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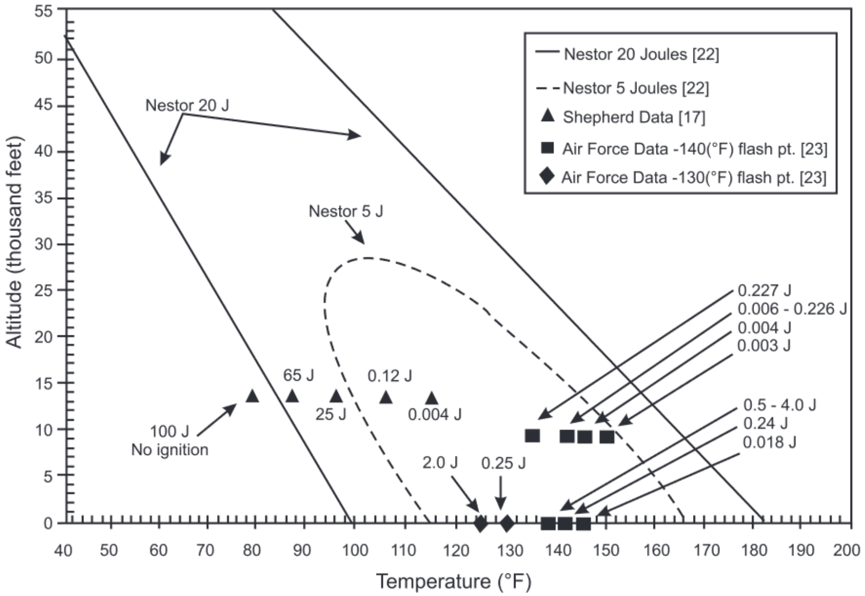
Flammability Limits

- In comparison to jet fuel, hydrogen is flammable over a much wider range of conditions:
  - Flammability width is 71% (jet fuel: 4.3%)
  - Cryogenic flash point guarantees flammability if it is vented
  - The high flash point of jet fuel and narrow flammability width dominates jet fuel flammability behavior
    - Example: JP-4 (flash point 0°F) was phased out in favor of the higher flash point JP-8 (flash point equivalent to Jet-A) because JP-8 is less hazardous

	Jet-A	Hydrogen[8]
Lower Flammability Limit	0.7%	4%
Upper Flammability Limit	5%	75%
Flash Point	≥100°F	-423°F



Jet-A Flammability Range [9]

[8]: M.G. Zabetakis. Flammability Characteristics of Combustible Gases and Vapors. USBM Bulletin 627. 1965.
[9]: A Review of the Flammability Hazard of Jet A Fuel Vapor in Civil Transport Aircraft Fuel Tanks. DOT/FAA/AR-98/26. 1998.

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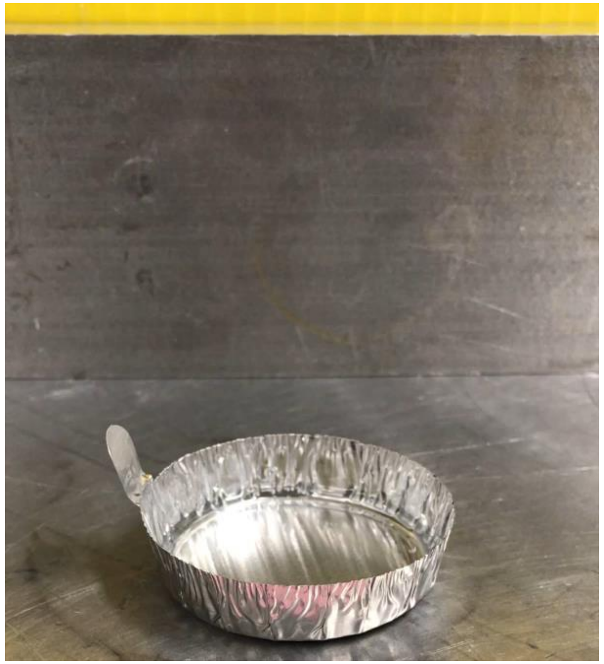
Flammability Limits – Case studies

Fuel: Jet-A (flash point ≥ 100°F) @ **Temperature < 100°F**

Result: low fire likelihood, zero explosion risk

- No flammable volume is present
- Local heat sources could increase the temperature to the flash point and then cause ignition



n-Decane, flash point = 115°F tested at room temperature

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Flammability Limits – Case studies

Fuel: Jet-A (flash point ≥ 100°F) @ **Temperature > 100°F**

n-Hexane, flash point = -15°F tested at room temperature

Result: moderate fire likelihood, low explosion risk

- Narrow flammability range → Flammable volume is limited to the location of liquid fuel
- If a fire occurs, the concentration of fuel results in high fire threat

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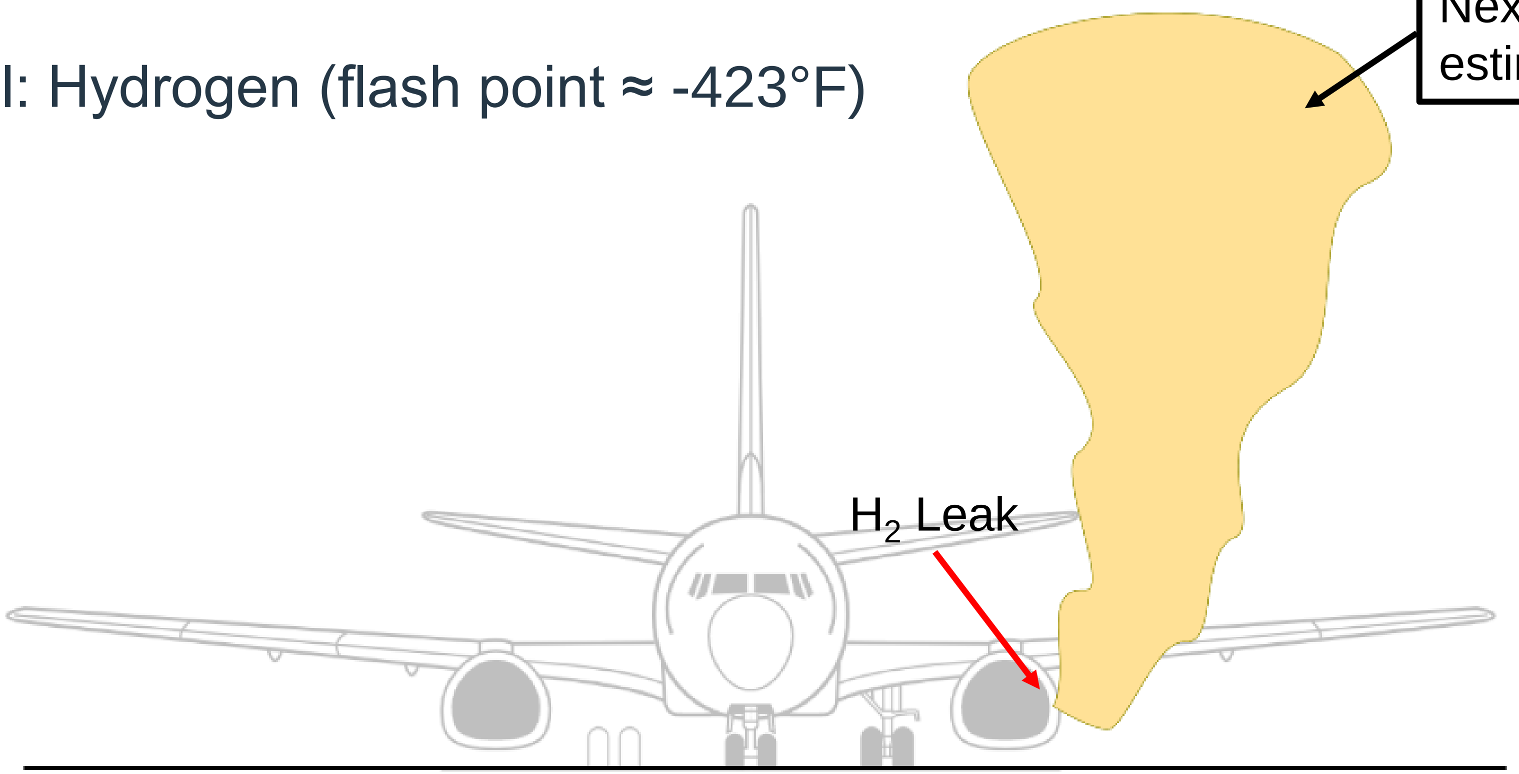
Flammability Limits – Case studies

Fuel: Hydrogen (flash point ≈ -423°F)



Hydrogen-air flame [10]

Result: high fire likelihood, high explosion risk

- High flammability range and rapid evaporation → Total flammable volume is high and the explosion threat is severe
- If ignition occurs, after the blast the low concentration in fuel results in a low fire threat

[10]: R.W. Schefer, W.D. Kulatilaka, B.D. Patterson, T.B. Settersten. Visible Emission of Hydrogen Flames. Combustion and Flame 156. 2009.

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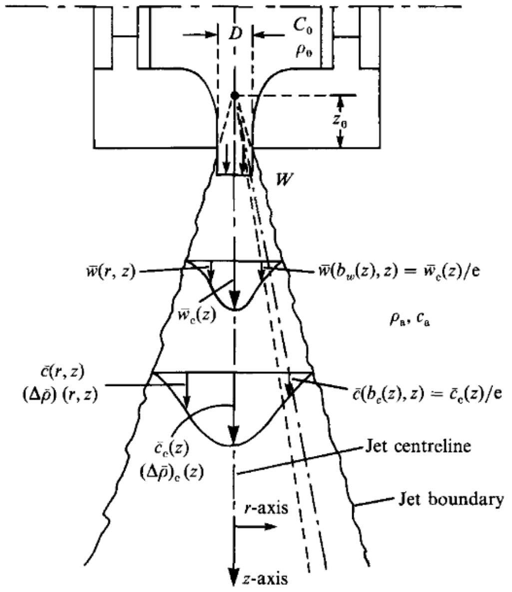
Flammability Limits – Case studies

- In the absence of wind and 3D effects, buoyant plumes can be solved via similarity solution
- Assume a H_2 leak with energy content = 1 gal/min Jet-A into Standard Temperature-Pressure (STP) Air



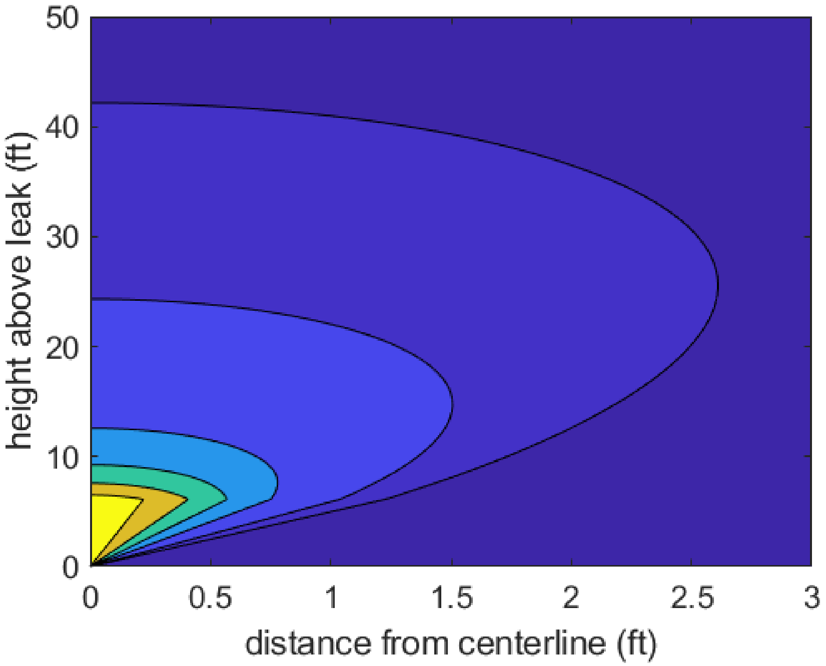
Flow Similarity Solution [11]

\+

Property	Value
Enthalpy Leak Rate	2.60 MJ/s
H_2 Volumetric Flux	0.265 m^3/s
Buoyancy Flux	2.43 m^4/s^3
Momentum Flux	139 m^4/s^2
Ambient Conditions	Air @ STP

Chosen Parameters

=



H_2 Concentration Solution

[11]: P.N. Papanicoloau, E.J. List. Investigations of Round Vertical Turbulent Buoyant Jets. J Fluid Mechanics 195. 1988.

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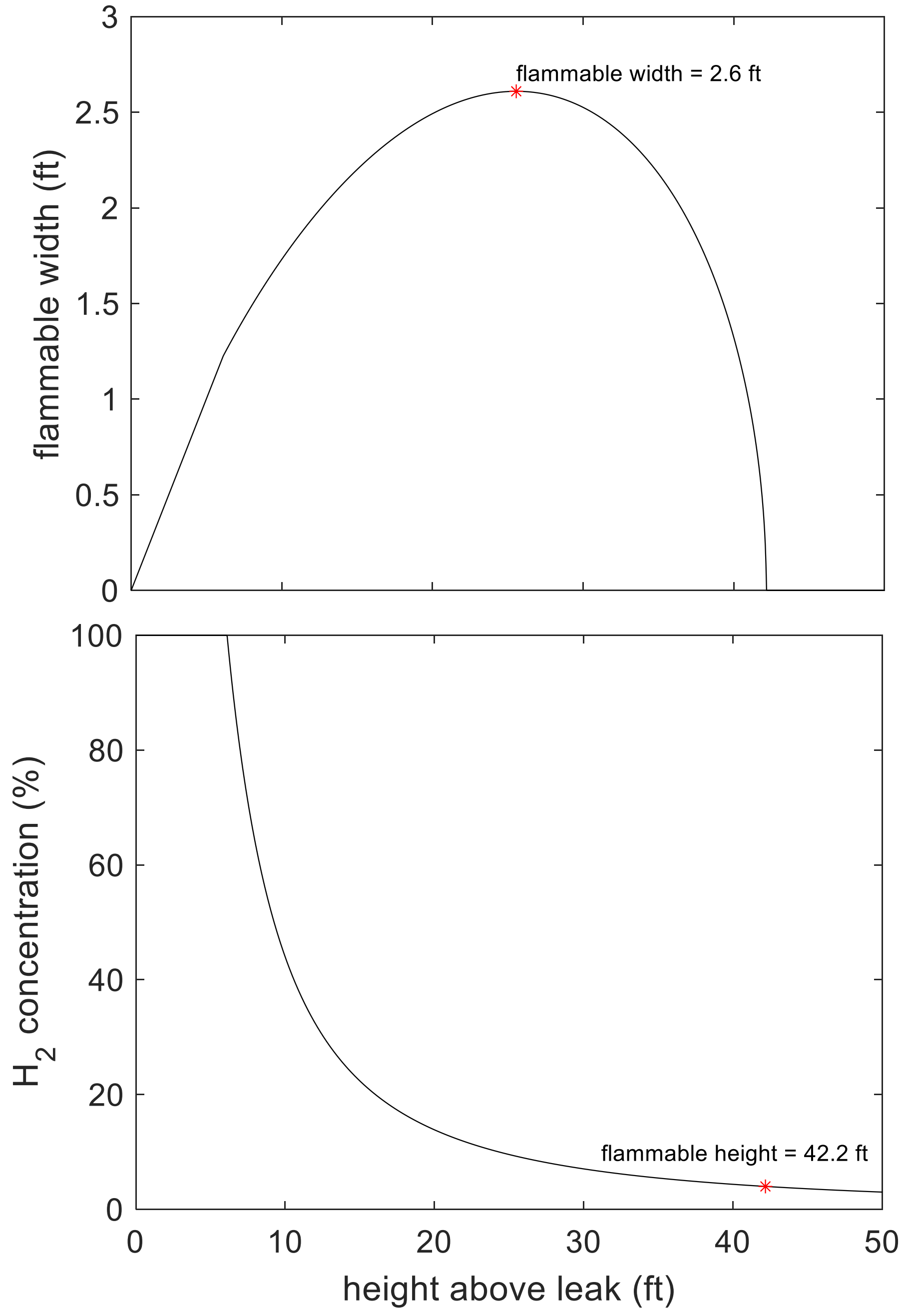
Flammability Limits – Case studies

- Similarity solution with these parameters predicts:
  - Flammable plume height = 42.2 ft
  - Maximum flammable width = 5.2 ft @ 25.6 ft above the leak
  - Total flammable volume = 543 ft^3
  - Blast energy content = 15.0 MJ → 5.6 lb TNT (detonation) or 1.4 lb TNT (no-detonation)
- Wind and 3D effects are expected to decrease this flammable volume
- Conclusion: The high volatility of hydrogen and broad flammability range result in a large flammable volume and a high explosion risk



Advantage: Jet Fuel

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Ignitability

Ignitability – Thermal

- Hydrogen has a significantly higher autoignition temperature (AIT) than jet fuel
  - H_2 AIT: 1085°F
  - Jet-A AIT: Accepted as 450°F
- → Flammable hydrogen/air mixtures could flow over hot surfaces with negligible ignition risk

Advantage: Hydrogen

Ignitability – Electrical

- Hydrogen has a significantly lower (more hazardous) Minimum Ignition Energy (MIE) than jet fuel
  - H_2 MIE: 19 μJ
  - Jet-A MIE: Accepted as 200 μJ
- This decrease in MIE dominates people's perceptions of ignitability – hydrogen/air mixtures can ignite from sources not expected to have been dangerous
  - Static charge
  - "Water hammer"
  - Friction sparks

Advantage: Jet Fuel

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Detectability

- Unlike jet fuel, hydrogen is odorless
- Safety analyses (e.g., [12]) emphasize the importance of hydrogen monitoring instrumentation to prevent accumulation and enable active purging
- Hydrogen leaks are readily detectable to 25% of the lower flammability limit with off-the-shelf equipment
- Although jet fuel is also detectable, because hydrogen is a pure substance with properties significantly different than other materials (e.g., solvents) hydrogen has the (slight) advantage

Advantage: Hydrogen

[12]: R.G. Zalosh, T.P. Short, P.G. Marlin, D.A. Coughlin. Comparative Analysis of Hydrogen Fire and Explosion Incidents. FMRC Report: RC78-T-41. 1978

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Storability

- Hydrogen is stored in a sealed container prone to over pressurization
  - Sealed liquid fuel tanks are prone to Boiling Liquid Expanding Vapor Explosions (BLEVE) [13]
- This motivates the requirement of a method to vent the hydrogen in an emergency
- However, rapid venting of hydrogen has been associated with accidental explosion
  - Require an improved understanding of high-speed emergency releases relevant to aerospace applications in order to determine maximum safe venting rates and effective hydrogen vent design criteria[14]
- Hydrogen is also a cryogenic fluid stored at -423°F

Advantage: Jet Fuel

[13]: Lees' Loss Prevention in the Process Industries (Fourth Edition). Editor(s): Sam Mannan, Butterworth-Heinemann. ISBN 9780123971890. 2012.
[14]: R.G. Zalosh, T.P. Short, P.G. Marlin, D.A. Coughlin. Comparative Analysis of Hydrogen Fire and Explosion Incidents. FMRC Report: RC78-T-41. 1978

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Flame Heat Flux

- The heat flux emitted by a flame may be calculated using the radiative heat fraction χ_R
  - χ_R may be calculated from the Planck-Mean Absorption Coefficient (a_p), flame residence time (τ_G), and flame temperature (T_f) via a semi-empirical formula [15]:

$$\chi_R = 9.45 \cdot 10^{-9}\left(a_p \tau_G T_f^4\right)^{0.47}$$

  - $a_{p,H2} \ll a_{p,hydrocarbons}$

Semi-Empirical Solution + Chosen Parameters =

Property	Value
Enthalpy Leak Rate	2.60 MJ/s
H_2 Volumetric Flux	0.265 m^3/s
Buoyancy Flux	2.43 m^4/s^3
Momentum Flux	139 m^4/s^2
Ambient Conditions	Air @ STP

Chosen Parameters

Calculated Radiative Heat Flux[16]

[15]: P.P. Panda, E.S. Hecht. Ignition and Flame Characteristics of Cryogenic Hydrogen Releases. Int J of Hydrogen Energy 42. 2017.
[16]: I.W. Ekoto, W.G. Houf, A.J. Ruggles, L.W. Creitz, J.X. Li. Large-Scale Hydrogen Jet Flame Radiant Fraction Measurements and Modeling. Proceedings of the 2012 9th International Pipeline Conference. 2012.

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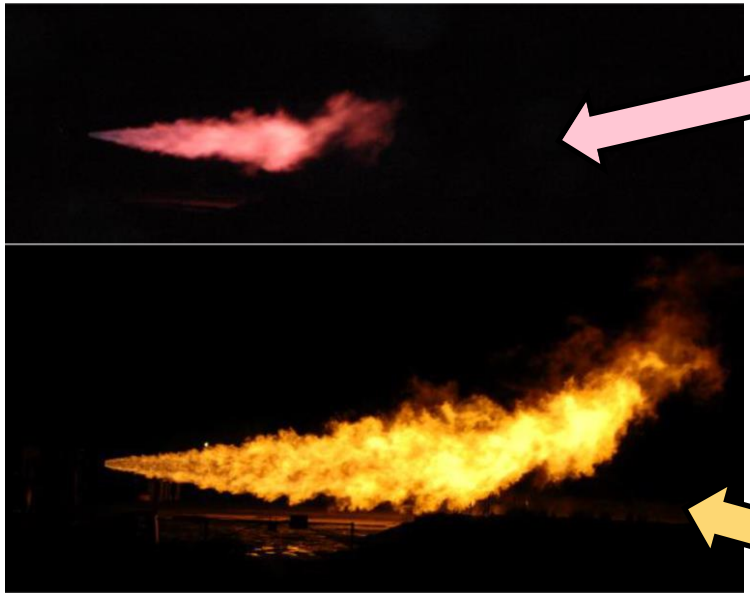
Flame Heat Flux

- Radiative heat flux is significantly reduced for hydrogen-air flames relative to hydrocarbon:
  - Hydrogen: $\chi_R \approx 0.06$
  - Propane: $\chi_R \approx 0.33$
- Hydrogen also does not form long-lasting pools
- → Fire threat is limited to the immediate vicinity of the leak with total heat transfer limited by the leak rate



Although hydrogen flames are hot, heat transfer is limited to convection

Soot produces high radiative heat flux

Images: Ekoto et al.[16]

Advantage: Hydrogen

[16]: I.W. Ekoto, W.G. Houf, A.J. Ruggles, L.W. Creitz, J.X. Li. Large-Scale Hydrogen Jet Flame Radiant Fraction Measurements and Modeling. Proceedings of the 2012 9th International Pipeline Conference. 2012.

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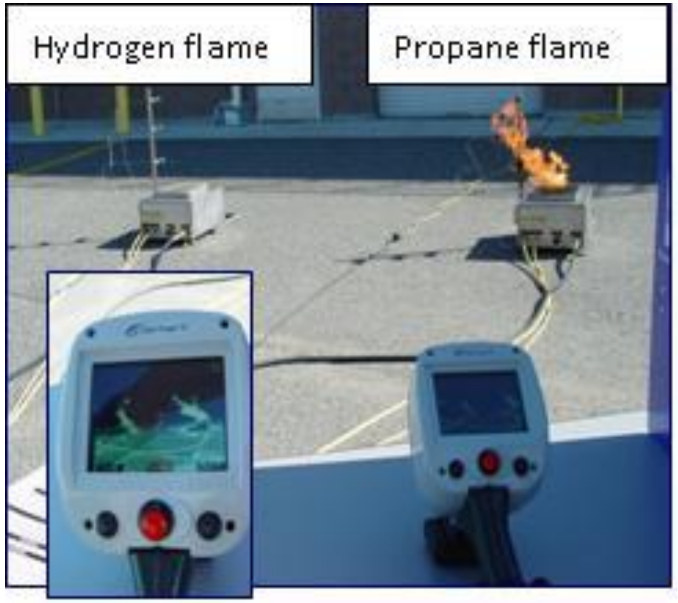
Invisible Flame?

- Hydrogen emits in the UV-wavelength, but the emission bands of water and the blue continuum result in a visible hydrogen flame[10]
- Hydrogen flames are less visible than hydrocarbon flames owing to the absence of soot
- Hydrogen flames may not be seen by human observers in bright conditions[17]
- Alternative means of detection (e.g., infrared cameras or additives) are available



[10]: R.W. Schefer, W.D. Kulatilaka, B.D. Patterson, T.B. Settersten. Visible Emission of Hydrogen Flames. Combustion and Flame 156. 2009.
[17]: https://h2tools.org/bestpractices/hydrogen-flames, accessed May 2022.

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Detonability and Ability to Explode

At ambient conditions hydrogen is detonable, jet fuel is not[18]

- Detonation produces peak pressures up to 650 psi
- Hydrogen is NOT expected to detonate in unconfined conditions[19]
- Hydrogen IS expected to detonate in confined conditions[13] (e.g., fuel tubes) if a detonable environment exists

In the case of an unconfined fuel-air explosion, the high flame speed of hydrogen will result in much larger pressures even if detonation does not occur

- Subsonic explosions produce blast waves equivalent to ≈25% that of a detonation
- Pressure load of a hydrogen explosion is equivalent to approximately 5% of an equivalent mass of TNT

Advantage: Jet Fuel

[13]: Lees' Loss Prevention in the Process Industries (Fourth Edition). Editor(s): Sam Mannan, Butterworth-Heinemann. ISBN 9780123971890. 2012.
[18]: C.S. Wen, K.M. Chung, W.H. Lai. Detonation initiation of JP-8-oxygen mixtures at different initial temperatures. Shock Waves 22. 2012.
[19]: H.G. Klug, R. Faas. Cryoplane: Hydrogen Fuelled Aircraft – Status and Challenges. Air Transport. 2001.

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Hydrogen vs Jet Fuel Safety Summary

- Hydrogen is more explosive and creates an explosive fuel-air mixture more readily
- Hydrogen fires will produce a weaker heat load on adjacent structures

Conclusions from Current Study

Item	Advantage
Flammability	Jet Fuel
Ignitability – Electric	Jet Fuel
Ignitability – Thermal	Hydrogen
Detectability	Hydrogen
Storability	Jet Fuel
Flame Heat Flux	Hydrogen
Detonability	Jet Fuel

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Proposed New Methodology

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“The usual precautions…”[1]

Zero Ignition Sources	• The fuel tank is assumed to always contain a flammable mixture → Extensive engineering design, analysis and certification testing are required to prevent ignition sources

Limit the Flammability	• The nitrogen generation system displaces oxygen in the fuel tank
	  • Reduces total time when an energy source could cause ignition
	  • Even when the tank is flammable, ignitability is reduced
	• Fuel seals and fittings designed to prevent the formation of flammable fuel/air mixtures

Other Contributing Factors	• Jet fuel is only flammable for a narrow range of conditions • Jet fuel is a liquid and vapors do not readily disperse → flammability is limited to where liquid is present

[1]: G.D. Brewer, R.E. Morris, G.W. Davis, E.F. Versaw, G.R. Cunnington, Jr., J.C. Riple, C.F. Baerst, G. Garmong. Study of Fuel Systems for LH2-Fueled Subsonic Transport Aircraft. Prepared under Contract NAS 1-14614 for NASA by Lockheed. NASA CR-145369. 1977 (volume 1) and 1978 (volume 2).

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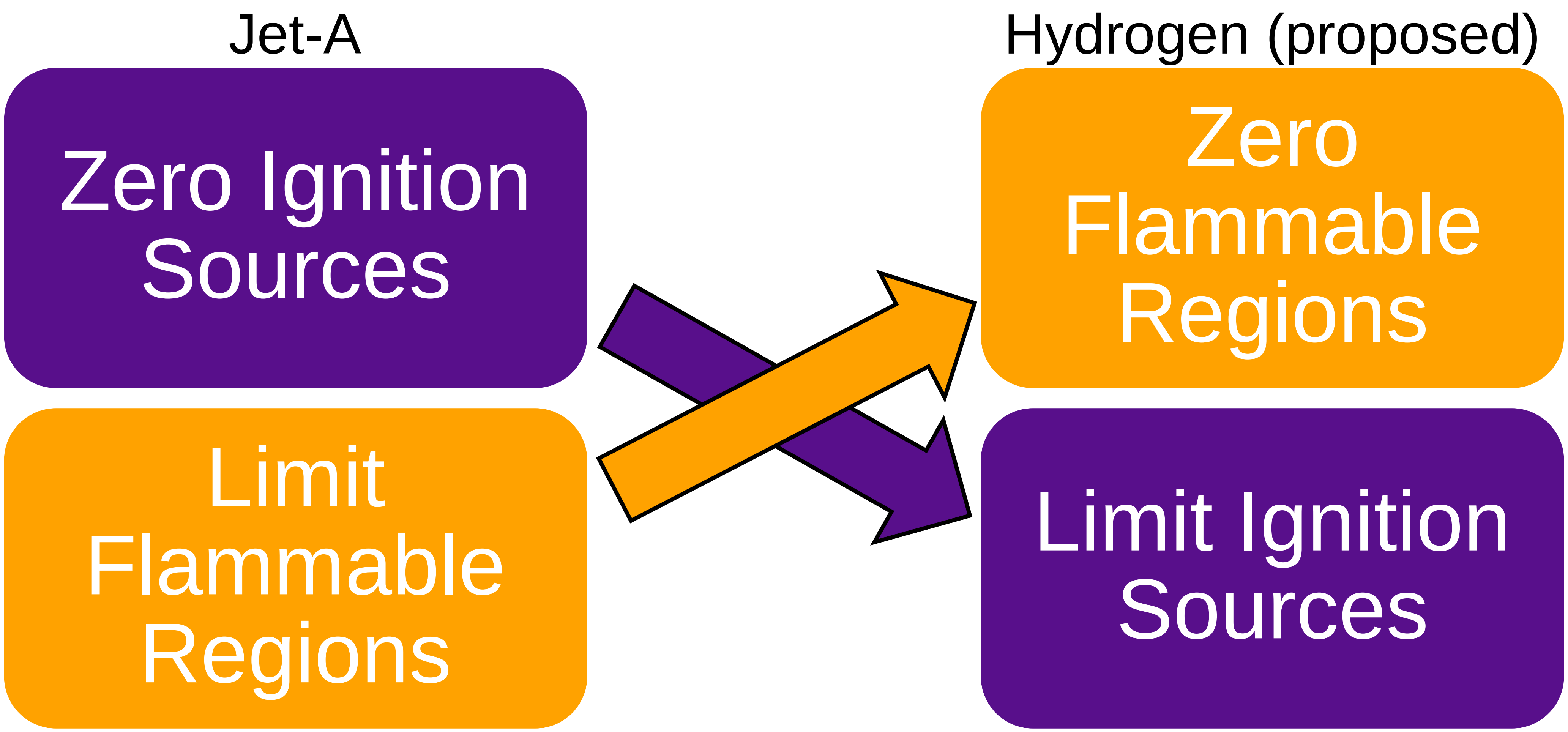
Proposed Methodology



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Proposed Methodology

Zero Flammable Regions	• The fuel system is built to never have ignitable regions by isolating the fuel from oxygen • If a leak occurs, then it is suppressed. E.g., detection and active ventilation
Limit Ignition Sources	• Design the fuel system to isolate potential energy sources from the fuel system
Other Contributing Factors	• H_2 rapidly disperses • H_2-specific detection systems exist and can detect H_2 at levels below the flammability limit • H_2 readily ignites from electric arcs, but, if the H_2 source is not flammable, a flame would flash and self-extinguish

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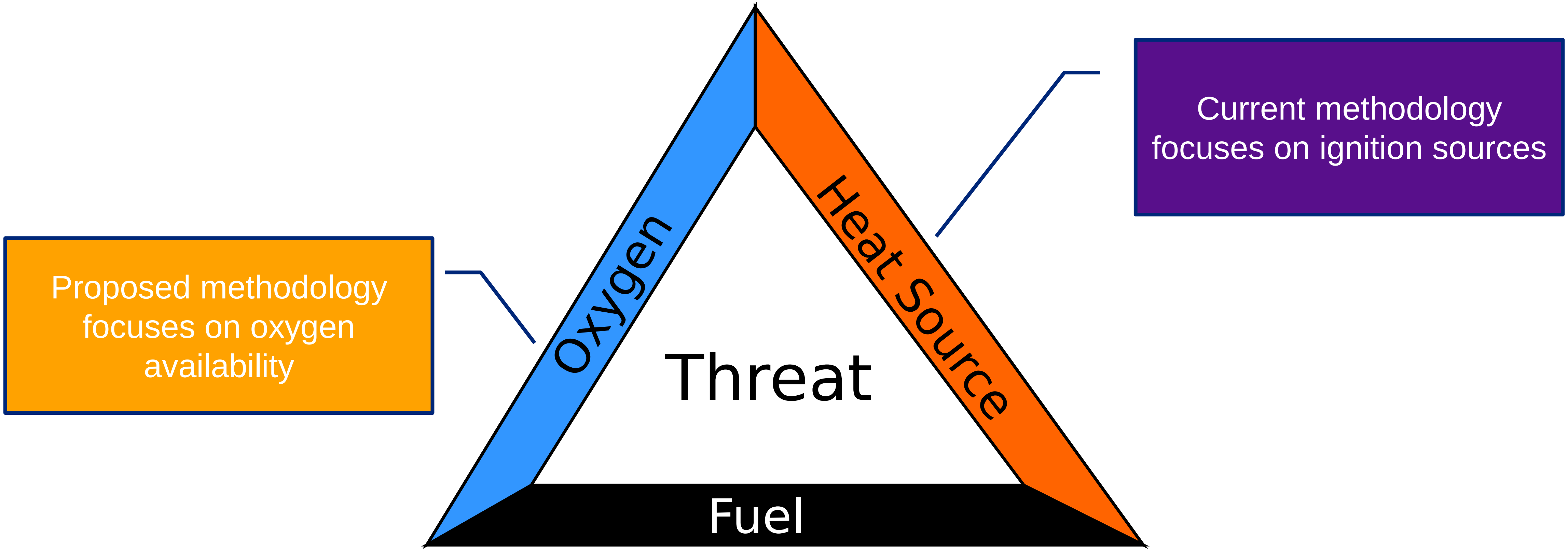
The Fire Triangle

- All three sides of the fire triangle need to be present to create a fire or explosion



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Conclusions

- Comparing Hydrogen to Jet Fuel:
  - Hydrogen explosions occur under a wider range of conditions at lower ignition levels and produce greater hazards
  - Hydrogen fires produce less radiative heating and are less dangerous to adjacent structures
- In order to make hydrogen equivalently safe to jet fuel, we need a system that is near 100% effective at preventing a flammable environment from being formed

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