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Safe Transition to Low Carbon Energy: Ammonia and Hydrogen

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Baker Engineering & Risk Consultants, Inc.

Presentation Overview

1. Background
2. Combustion Parameters
3. Explosion Basics
4. Comparison of Risks
5. Key Takeaways

Large Cloud VCE Test at BakerRisk's BCTF

BakerRisk

- 100% Employee Owned
  - Over 35-years experience "Providing Solutions to Manage Hazards and Risks"
- Over 100 engineers and scientists
  - Average individual experience of over 20 years

www.bakerrisk.com

Locations: San Antonio, Houston, Chicago, Los Angeles, Canada, United Kingdom

Robert Magraw
Operations Manager, BakerRisk Europe Ltd.

- 18+ years in the nuclear industry
- 14+ years BakerRisk – oil, gas and chemicals

PHA (HAZOP/LOPA/SIS/SIL) Studies
Quantitative Risk Assessment
Process Safety Management and Auditing
Insurance Risk Engineering
Accident Investigation

Certified Functional Safety Engineer
IChemE Hazard Technical Committee member
EPSC Technical Steering Group member

Background – Why NH_3 and LH_2

- Hydrogen and Ammonia offer "carbon-free" emissions
  - Multiple "colors" based on source of the hydrogen

- H_2 and NH_3 can provide "long" term energy storage and transport solutions

Techno-Economic Challenges of Green Ammonia as an Energy Vector

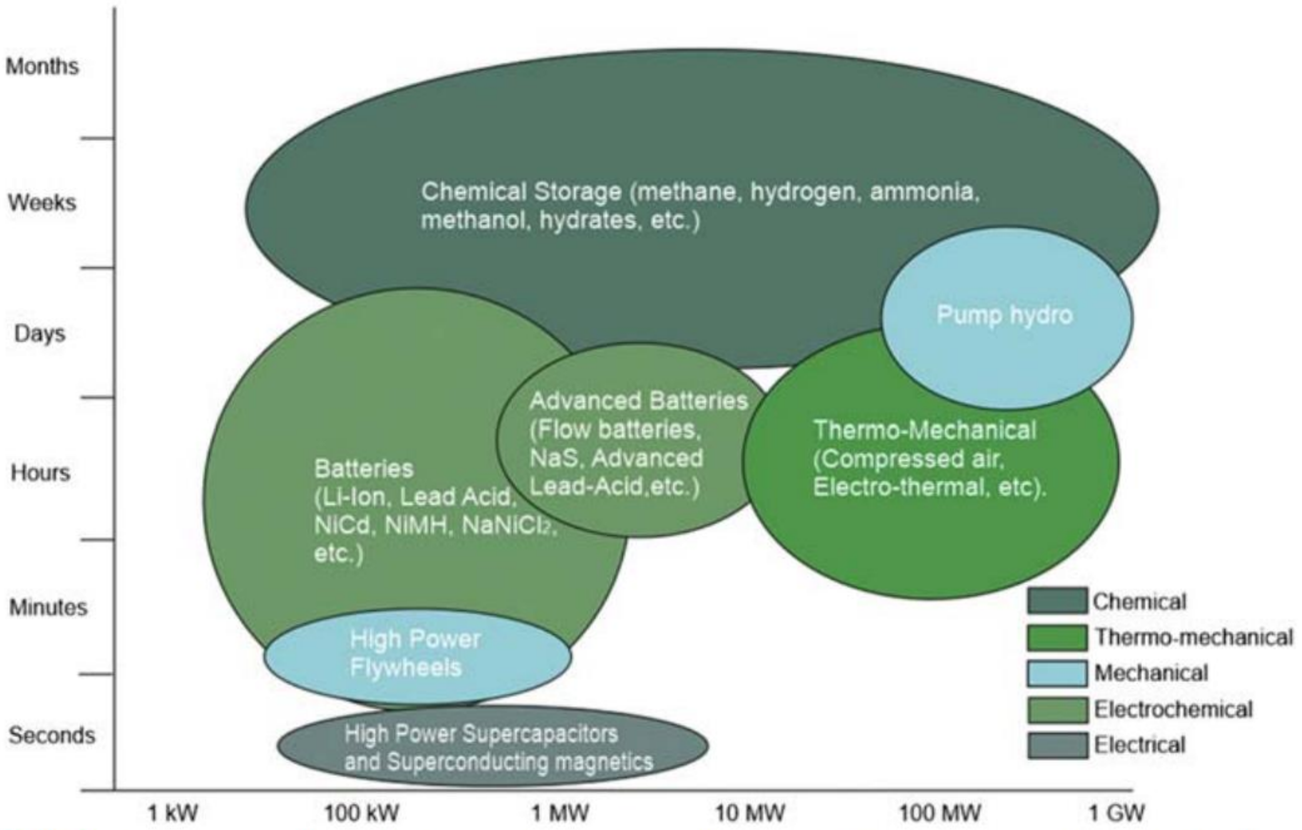
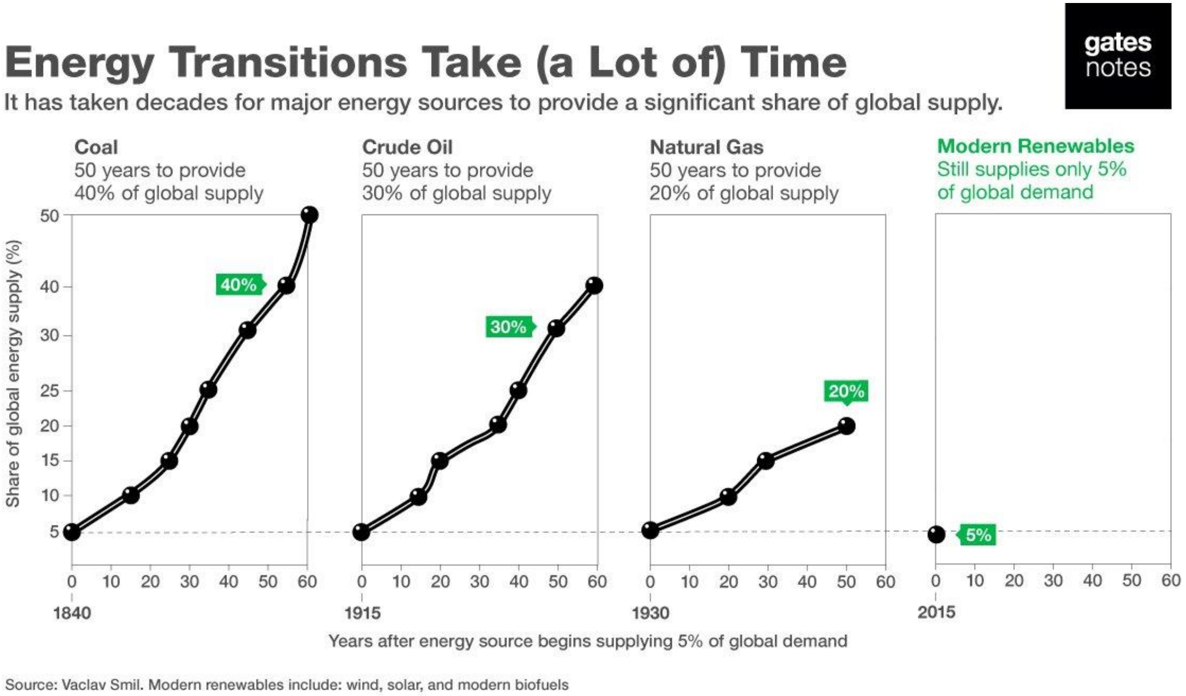


FIG. 1.6 Power versus time of storage. Comparison between different energy storage technologies.

Background – Global Energy Trends



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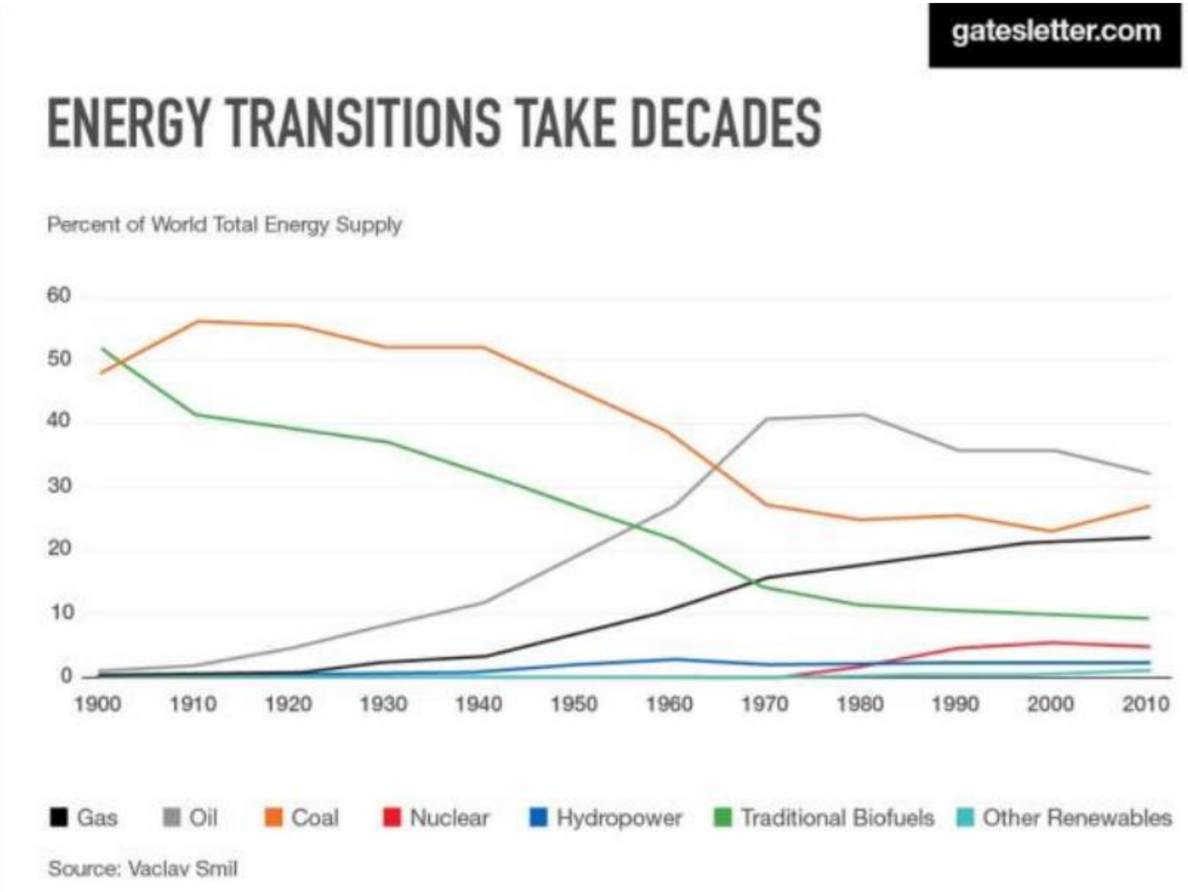


https://www.businessinsider.com/bill-gates-interview-energy-miracle-coming-2016-2?r=US&IR=T

Background – Energy Transition

- Collaborative effort across the world to "net zero" mandates
- UK/EMEA, Australia and Japan are actively preparing for transport of ammonia and liquid hydrogen
- Both fuels pose significant design challenges with respect to safe operation

Blue ammonia shipped from Saudi Arabia to Japan
https://www.aramco.com/en/news-media/news/2020/first-blue-ammonia-shipment

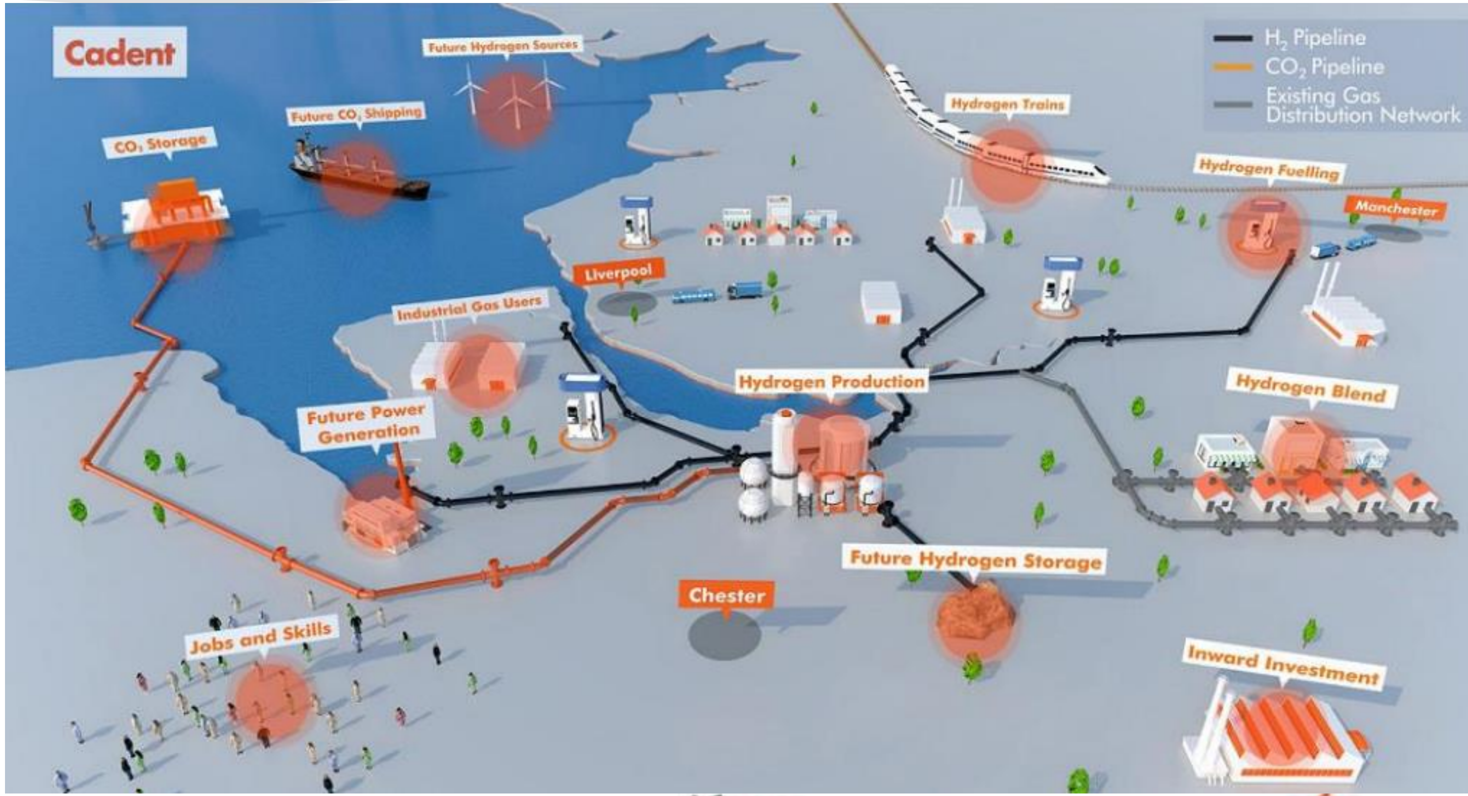
LH2 from Australia to Japan
https://global.kawasaki.com/en/stories/hydrogen/

UK Projects – H2 Teesside / Net Zero Teesside / Zero Carbon Humber

- Plans underway for UK's largest blue hydrogen production facility, targeting 1GW of hydrogen production by 2030
- Final investment decision (FID) in 2024
- CCS stored in Endurance, UK's largest appraised saline aquifer for carbon storage

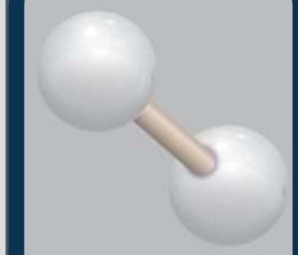
UK Projects – Hynet

- Hydrogen production
- Transition of industrial users to hydrogen
- CCS

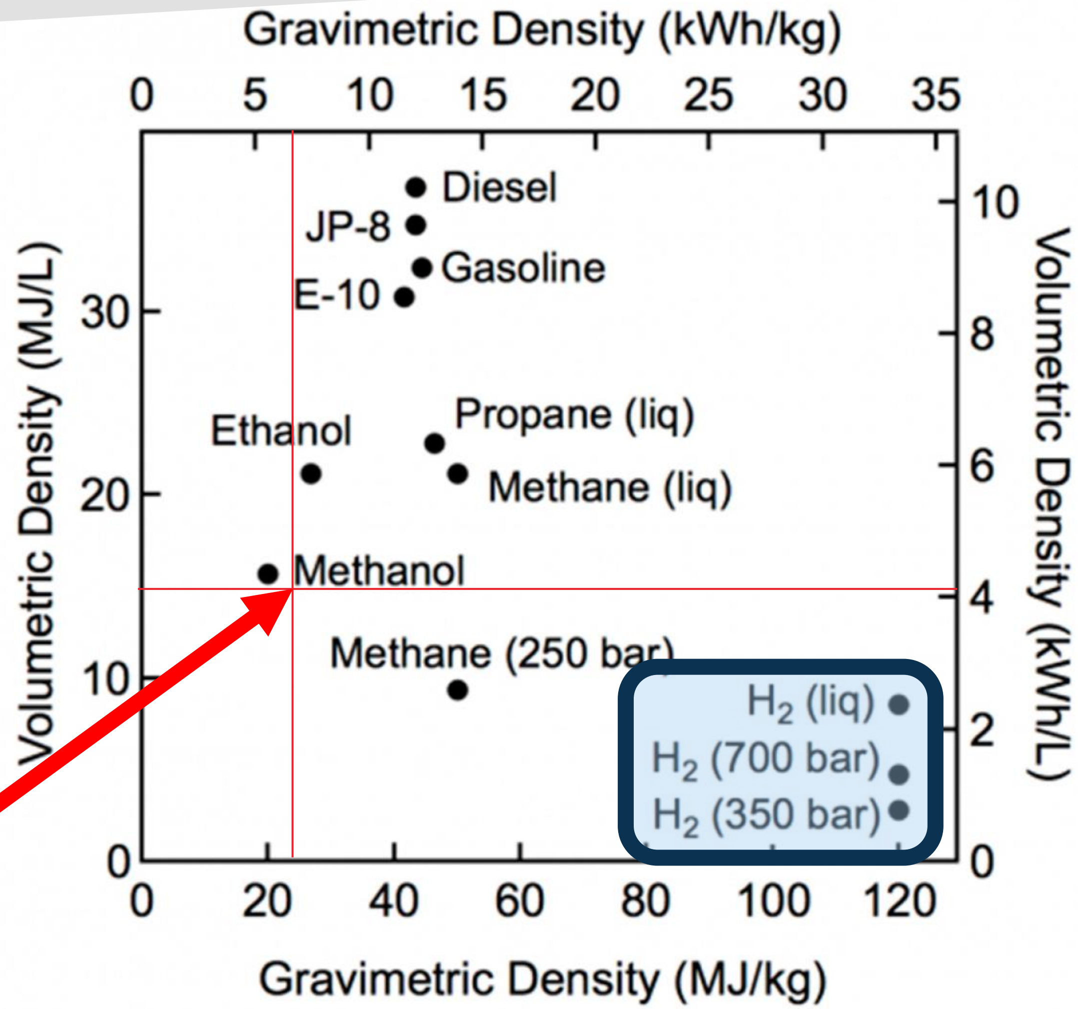


Cadent Your Gas Network CF eni.com ESSAR OIL UK Hanson HEIDELBERGCEMENTGroup inovyn An INEOS company PROGRESSIVE ENERGY

Energy Content

	 HYDROGEN, H_2	 AMMONIA, NH_3
Volumetric energy density (MJ/L)	10 $_{(l)}$, 6 $_{(g,\ 700\ bar)}$	14$_{(l)}$
Gravimetric energy density (MJ/kg)	142	23
Flammability limit (Equivalence ratio)	0.10–7.1	0.63–1.40
*Flammability hazard**	4	1
*Health hazard**	0	3

** National Fire Protection Association (NFPA) 704 classification*



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https://www.mdpi.com/ChemEngineering/ChemEngineering-03-00087/article_deploy/html/images/ChemEngineering-03-00087-g001.png

Key Takeaways – Hydrogen Economy

1 Apparent Low / No-Carbon Mandate

We are seeing a global infrastructure investment in liquid hydrogen and ammonia transport

2 Hydrogen and Ammonia are Options

Both molecules are carbon-free energy carriers. The end goal is "Liquid Sunshine"

3 Both Fuels Have Unique Properties

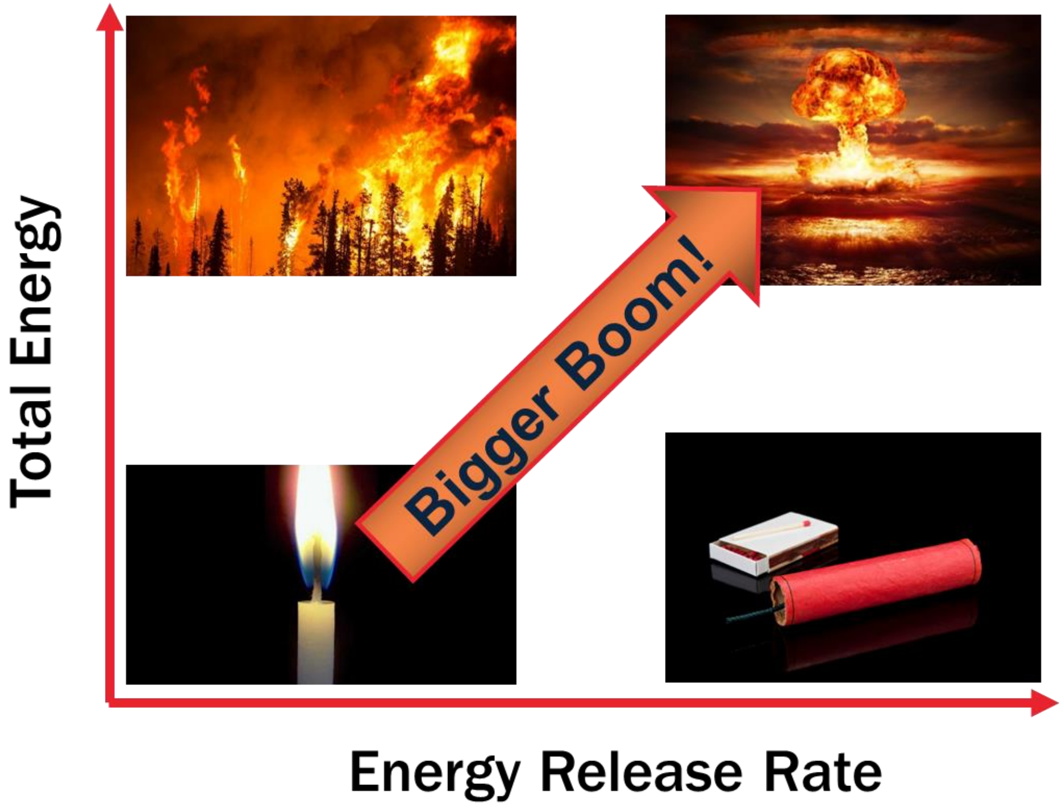
Volumetric and gravimetric energy density impact storage and transport costs, as well as end use

Fundamental Design Parameters

- Total Energy Content
  - Candle vs. Forest fire
  - Firework vs/ Atomic bomb

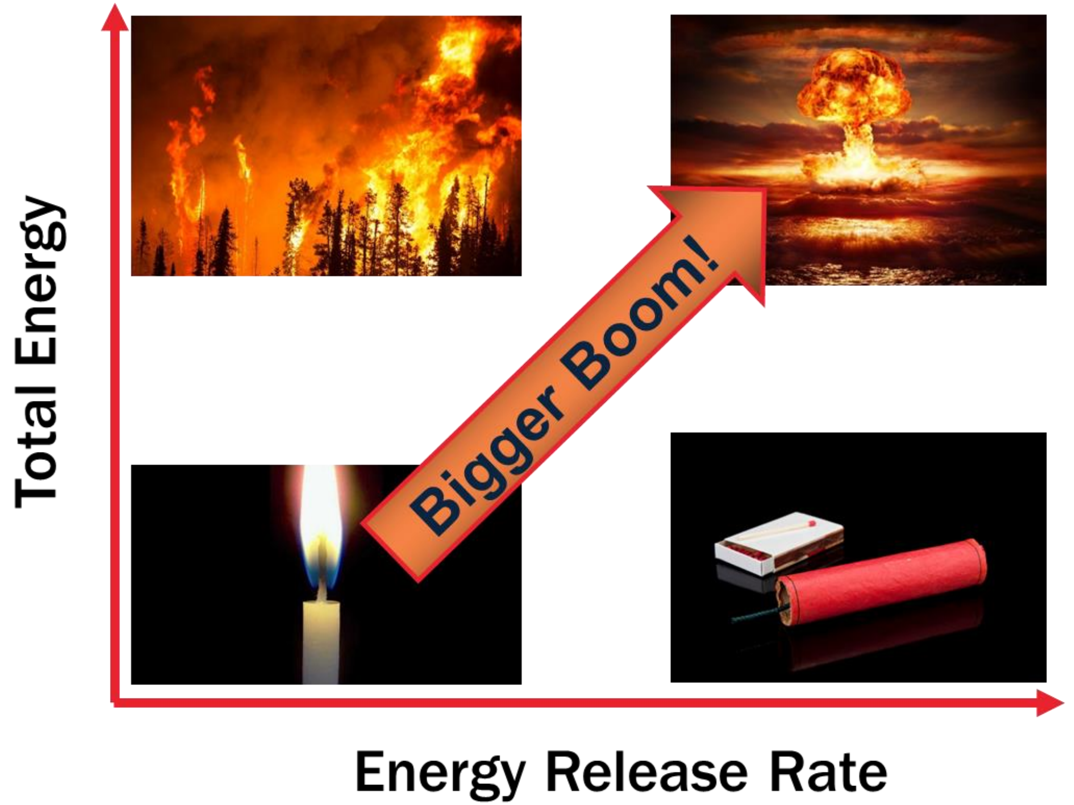
- Energy Release Rate
  - Candle vs. Firework
  - Forest Fire vs. Atomic bomb

- Stand-off distance from Energy Release Point to Target
  - Stand-off distance can be scaled by explosion energy



Fundamental Design Parameters

Parameter	Ammonia	Methane	Hydrogen
Minimum Ignition Energy (MIE) [mJ]	680	0.3	<0.1
Lower Flammability Limit (LFL) [vol%]	15	5	4
Upper Flammability Limit (UFL) [vol%]	28	15	75
Pmax Fuel Concentration [vol%]	23	10	35
Laminar Burning Velocity (LBV) [cm/s]	10	40	312
Heat of Combustion [MJ/m³]	2.9	3.1	2.6
Gravimetric Energy Density [MJ/kg]	23	54	142
Volumetric Energy Density [MJ/L]	14	22	10



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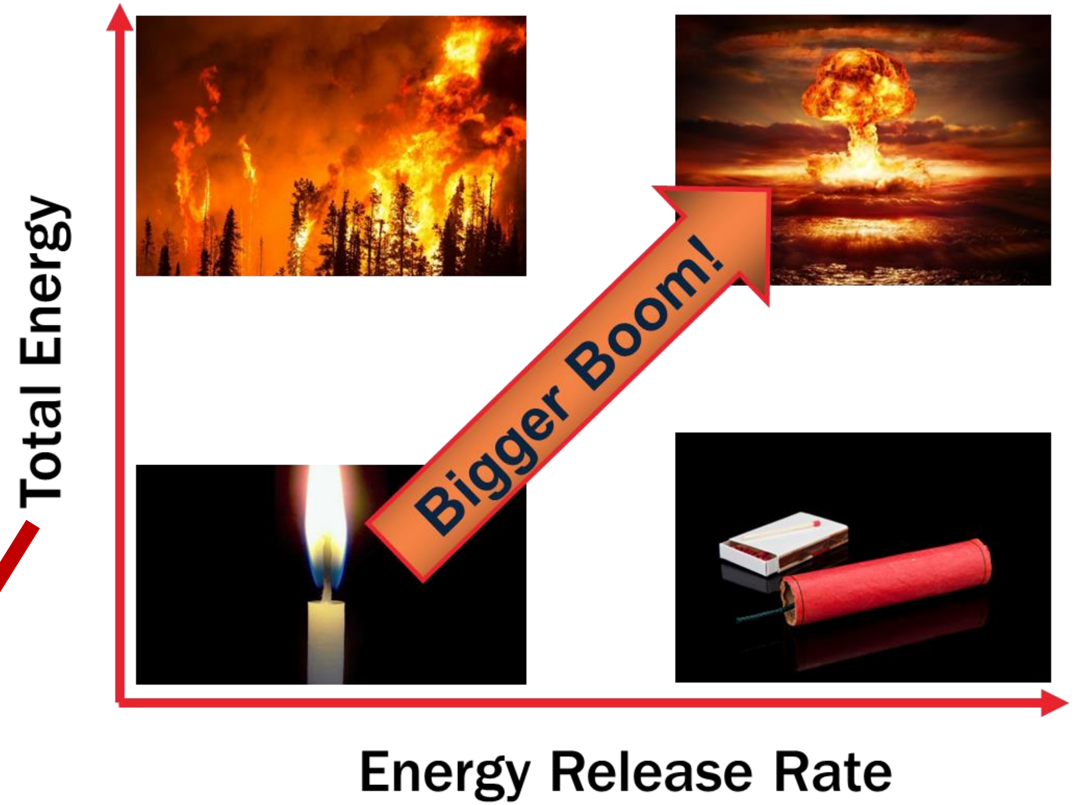

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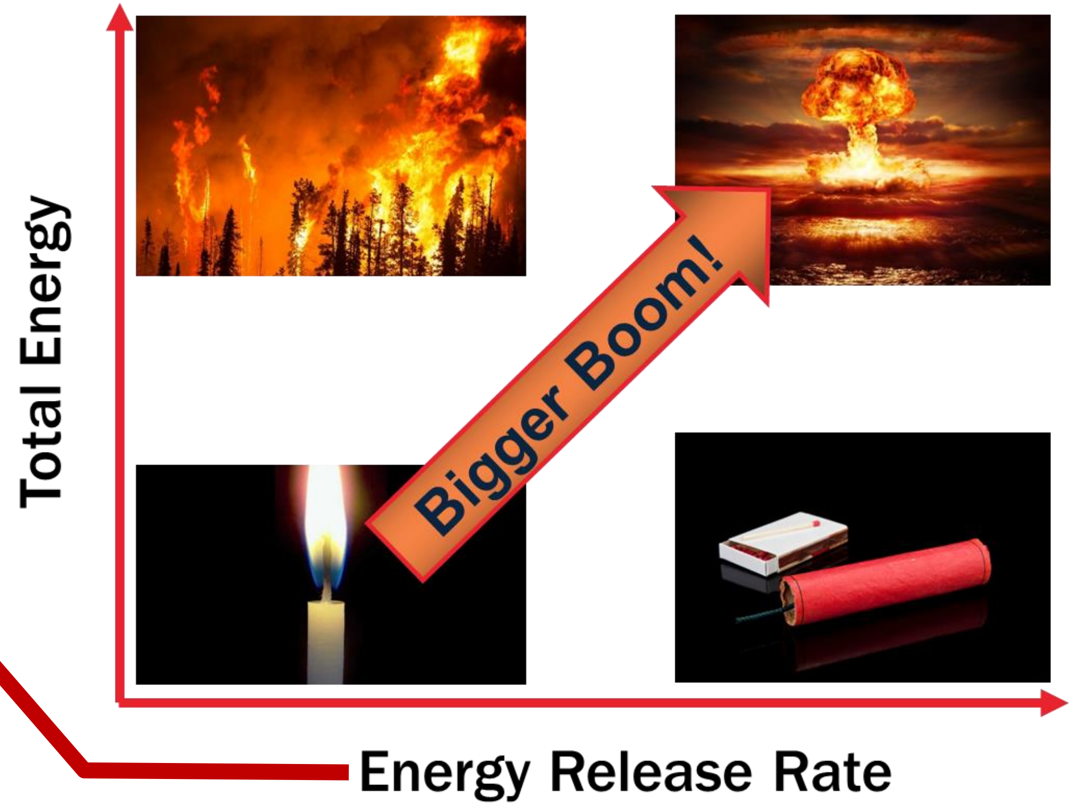
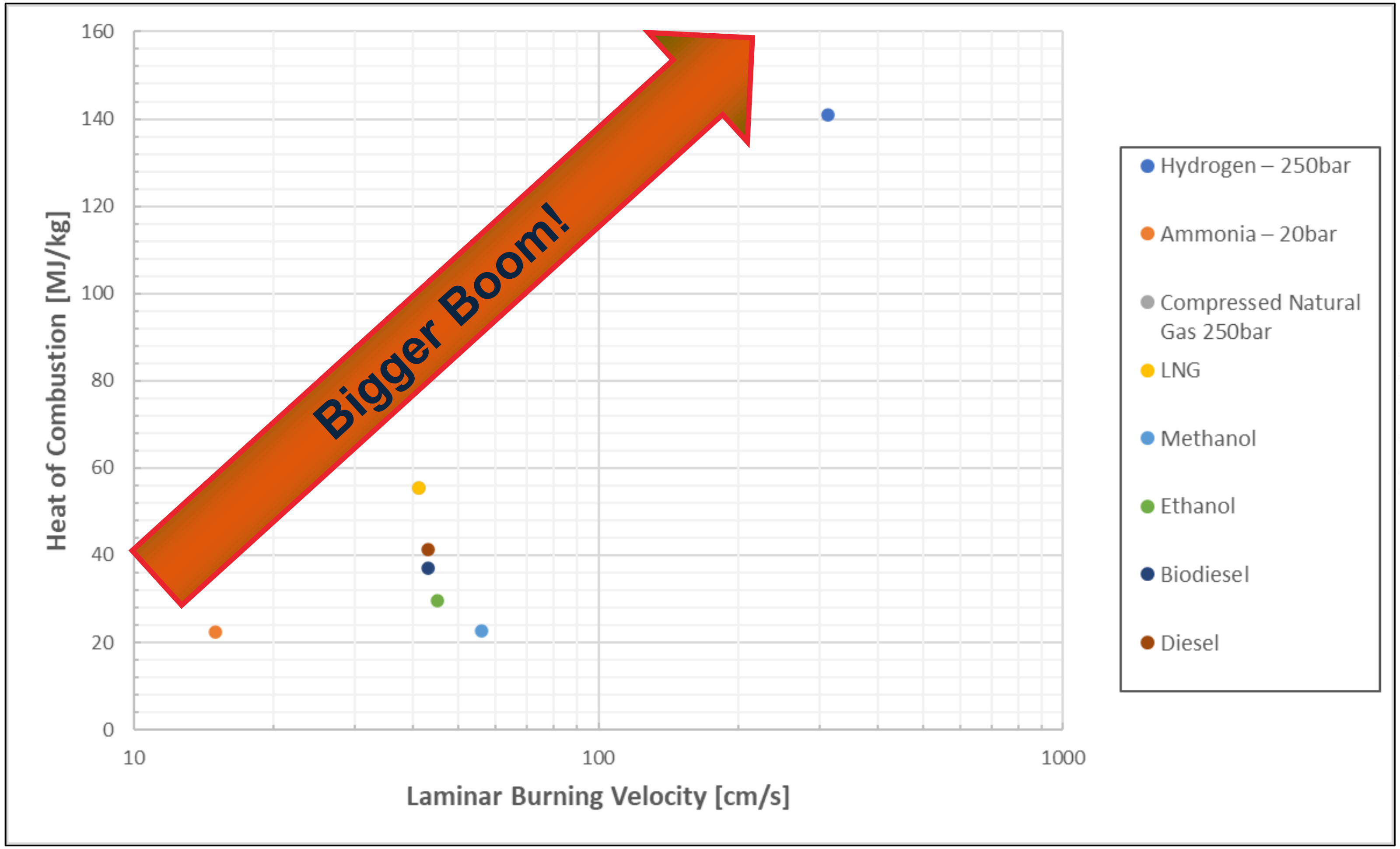
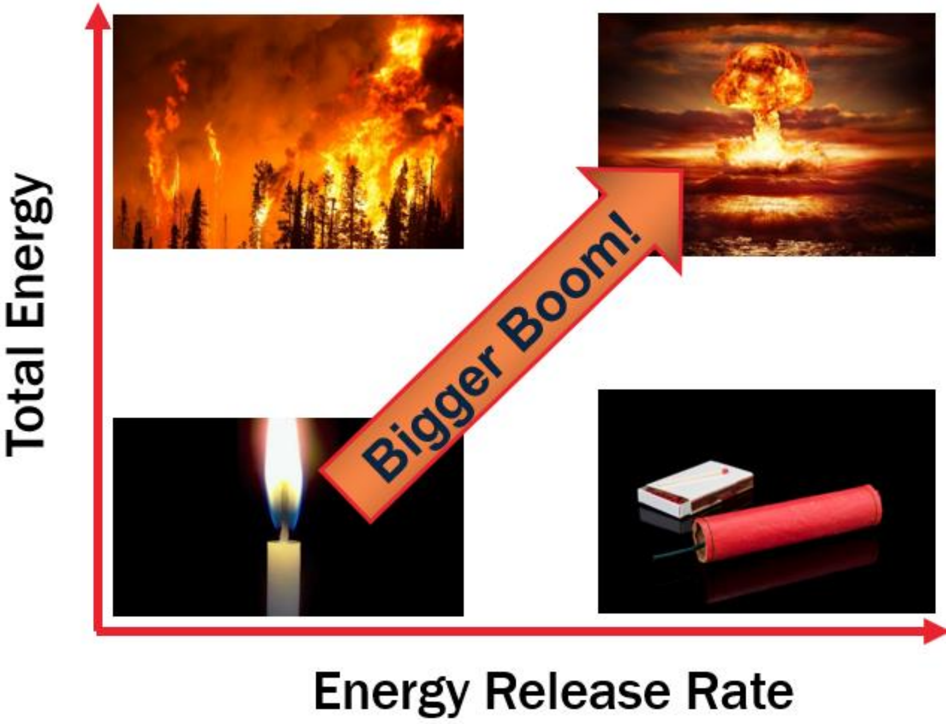


Heat of Combustion vs. Log Laminar Burning Velocity





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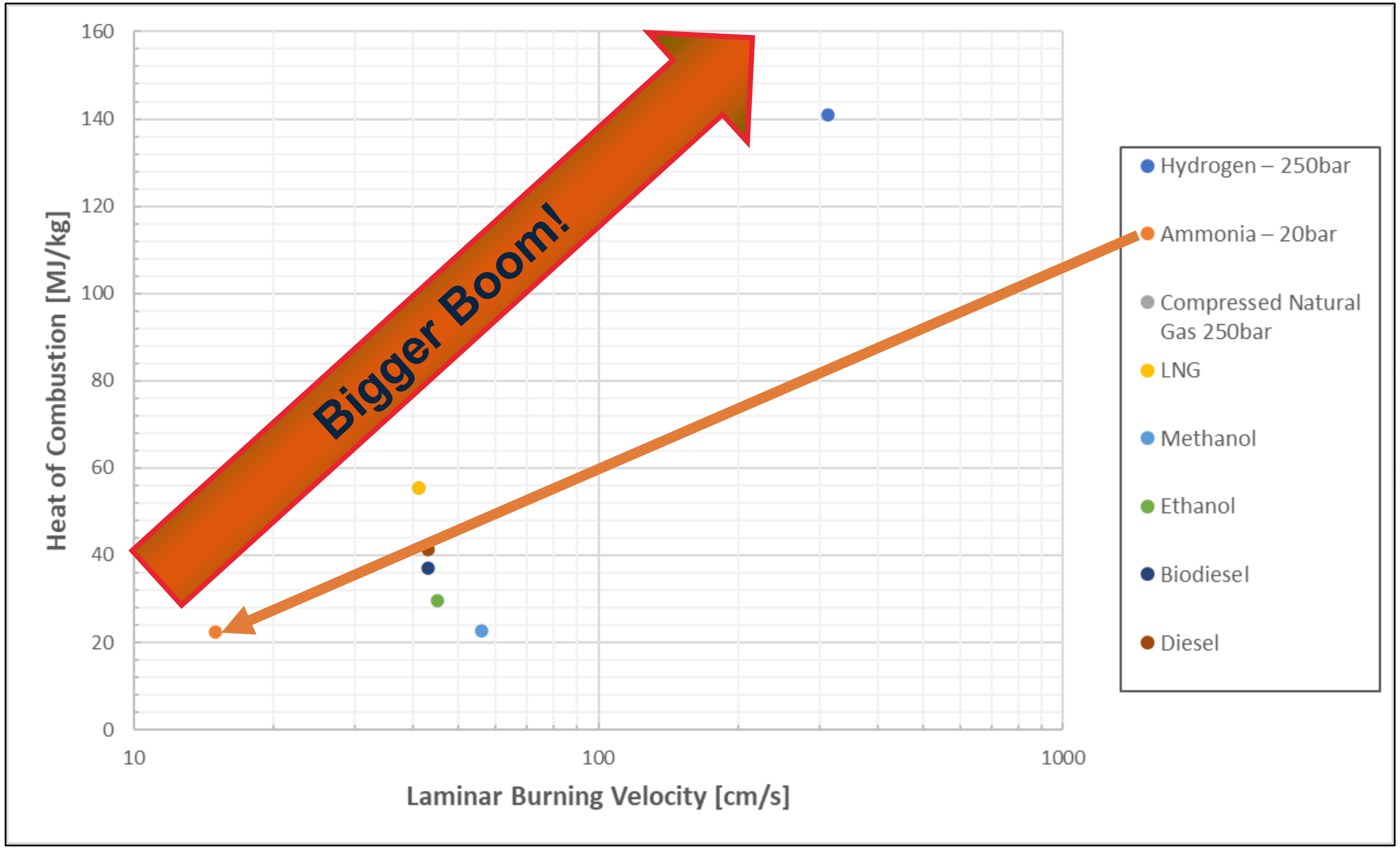

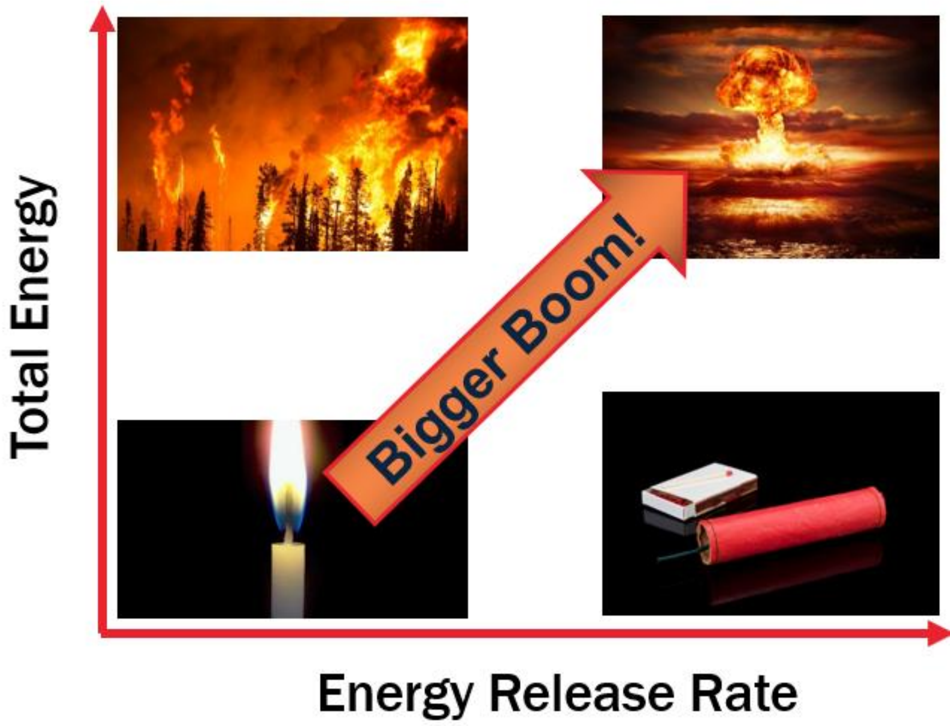

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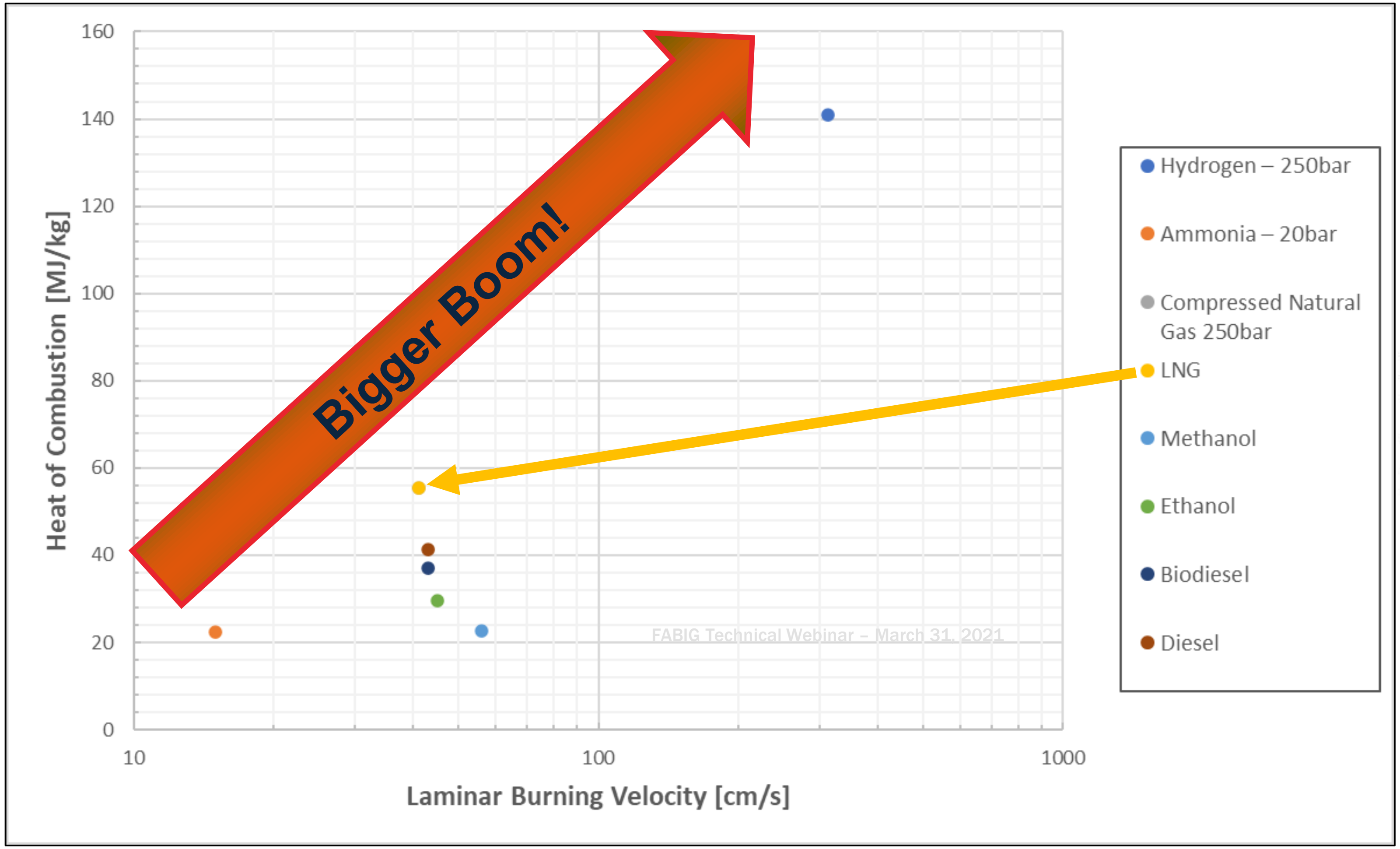

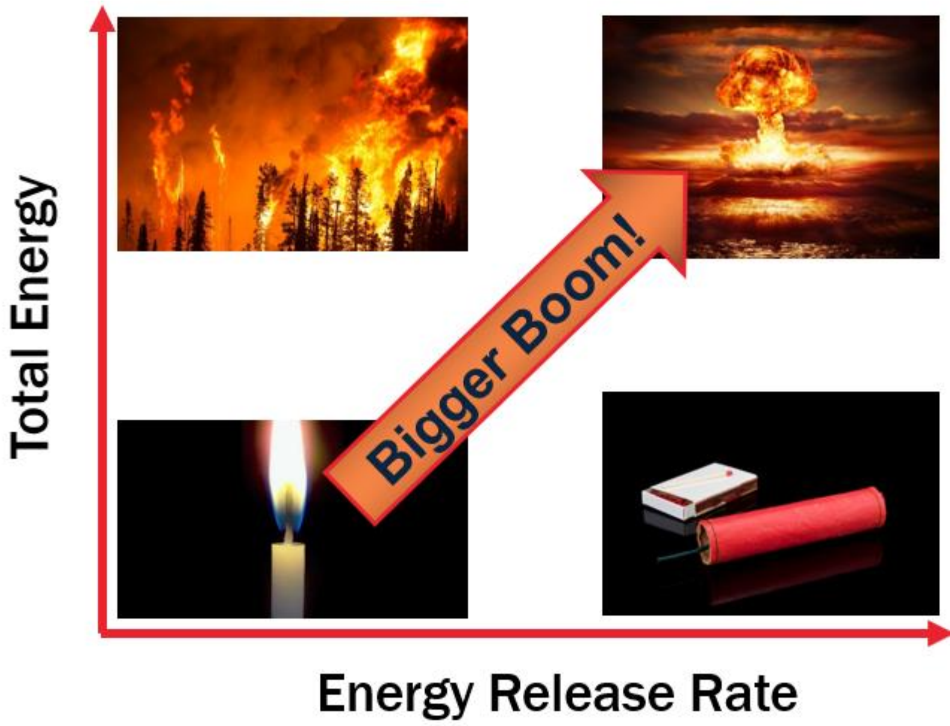

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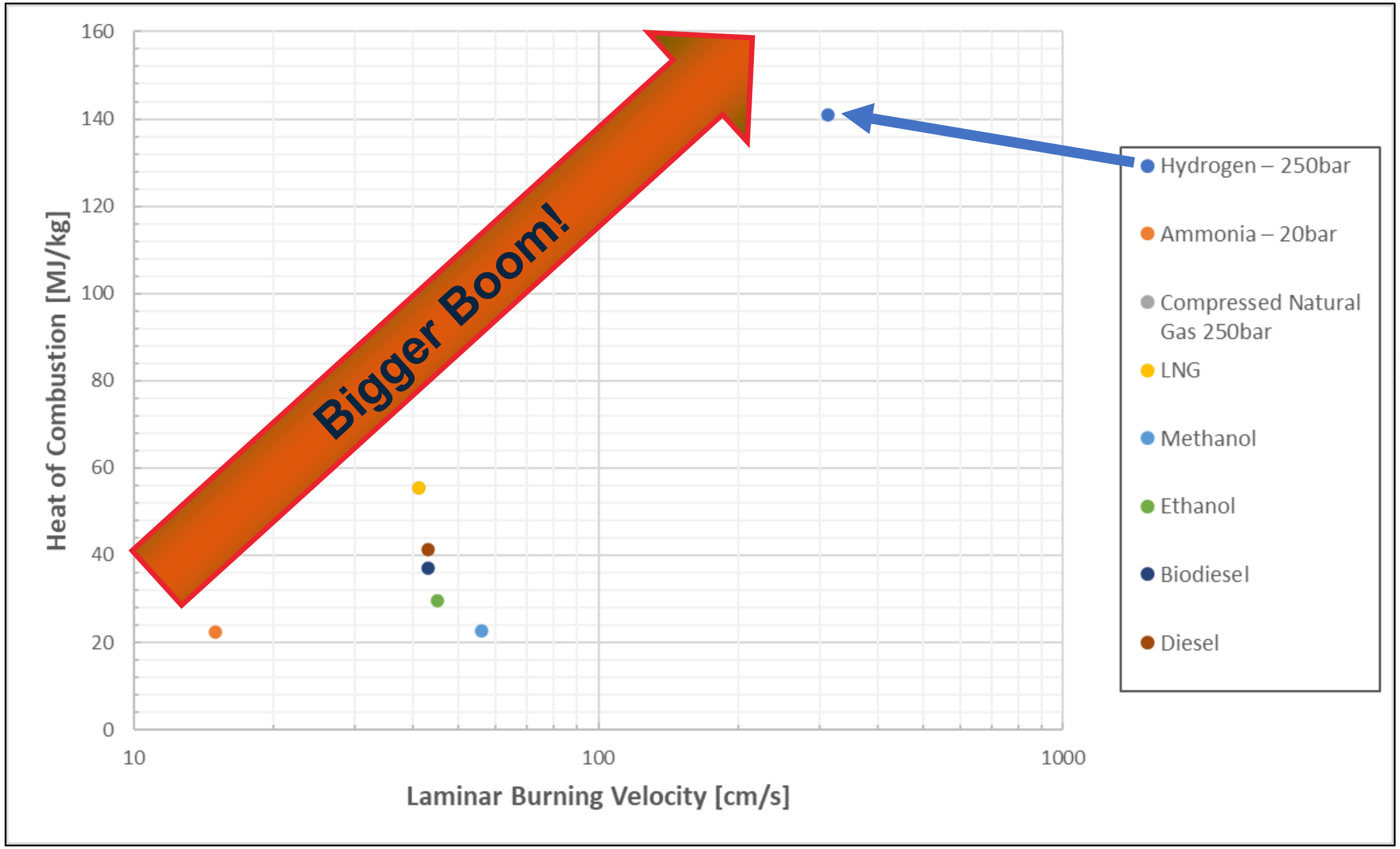
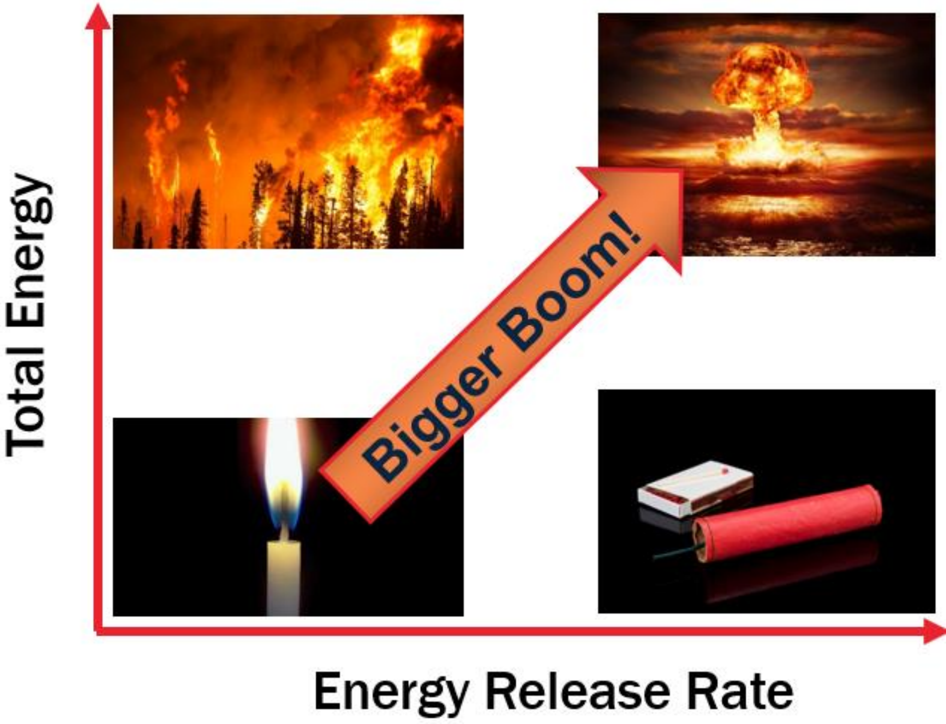
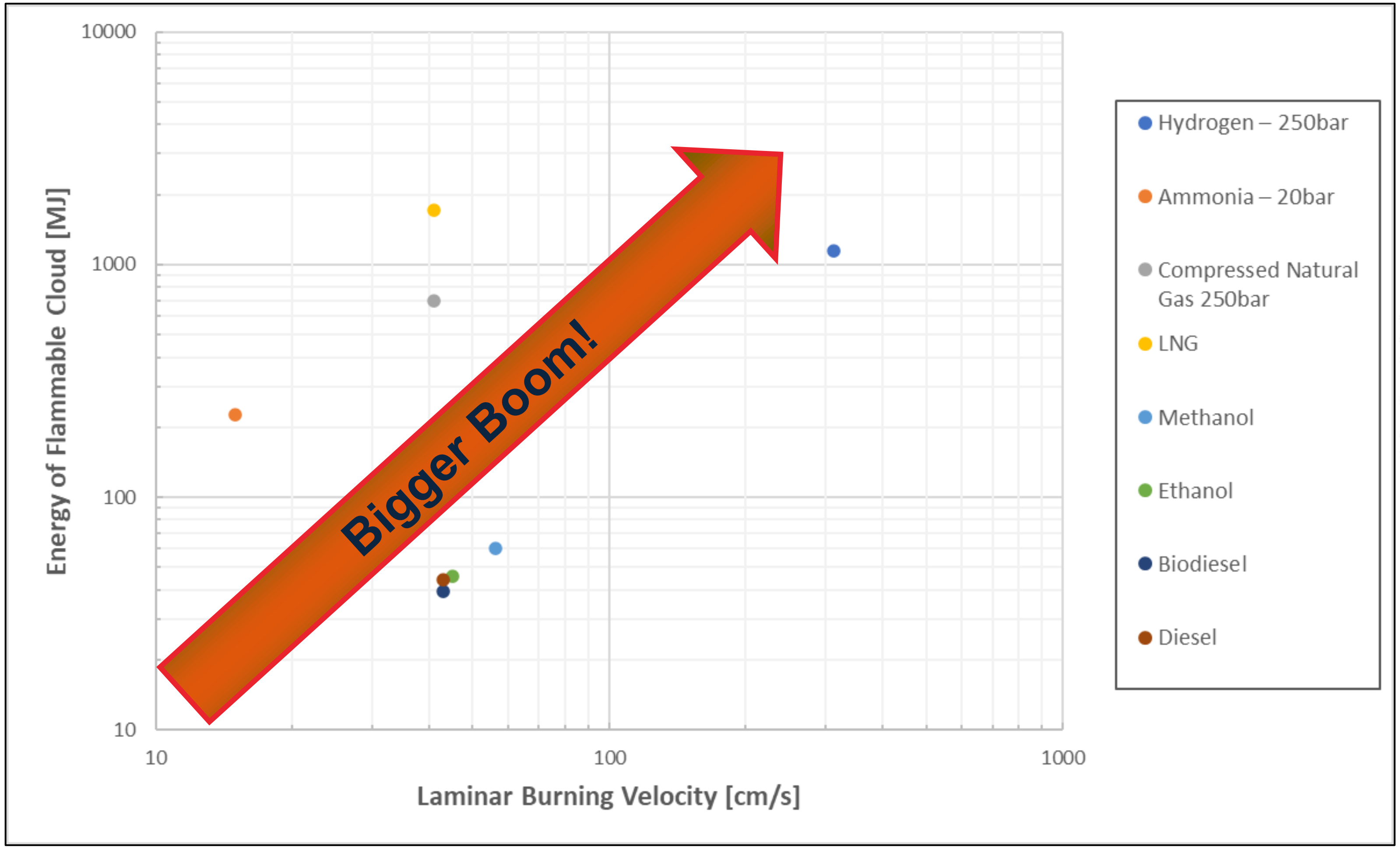
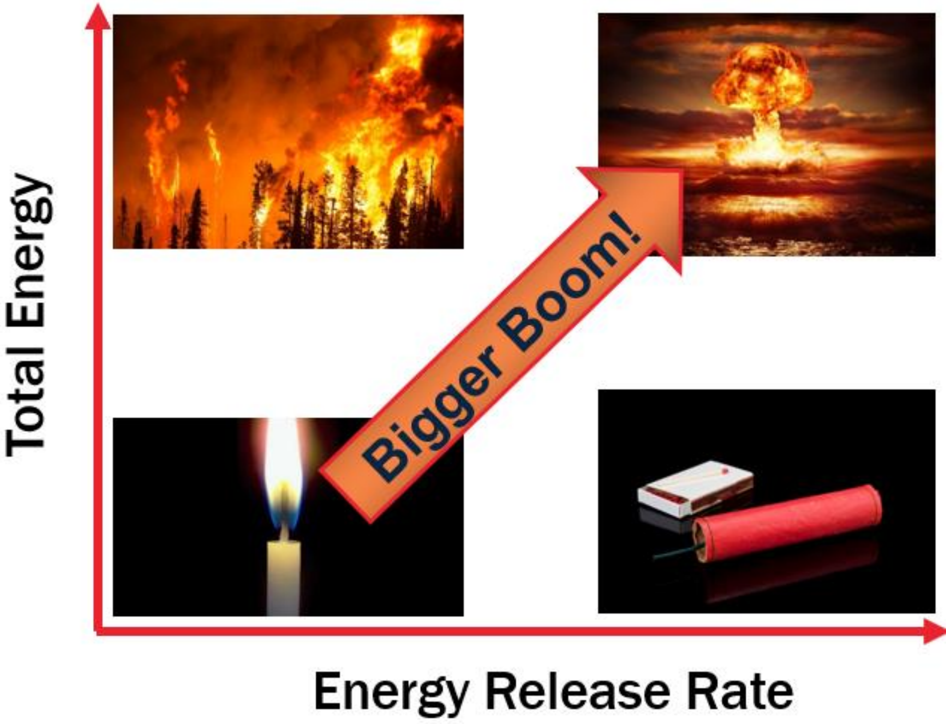




Predicted Flammable Cloud from 2-inch Release





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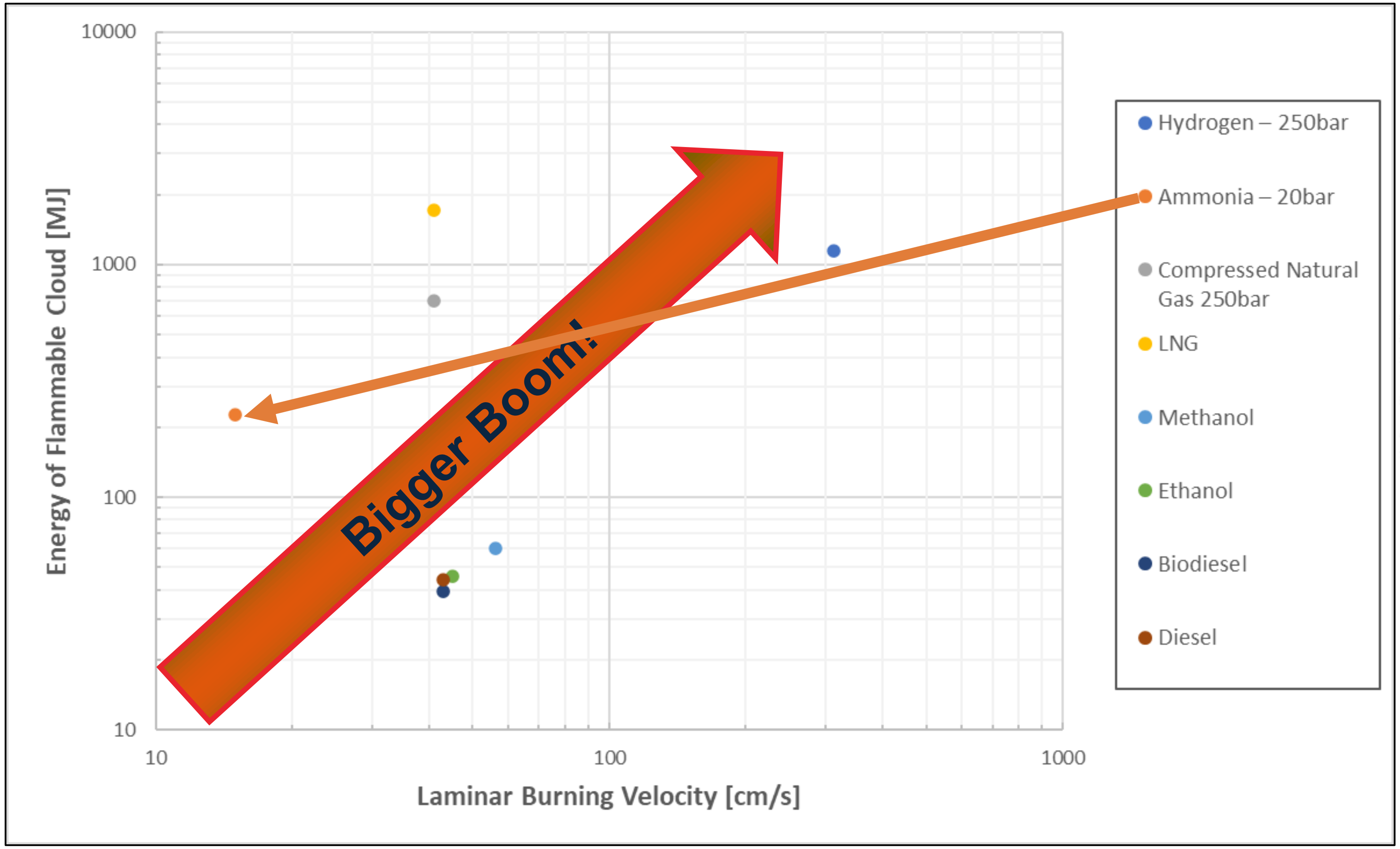

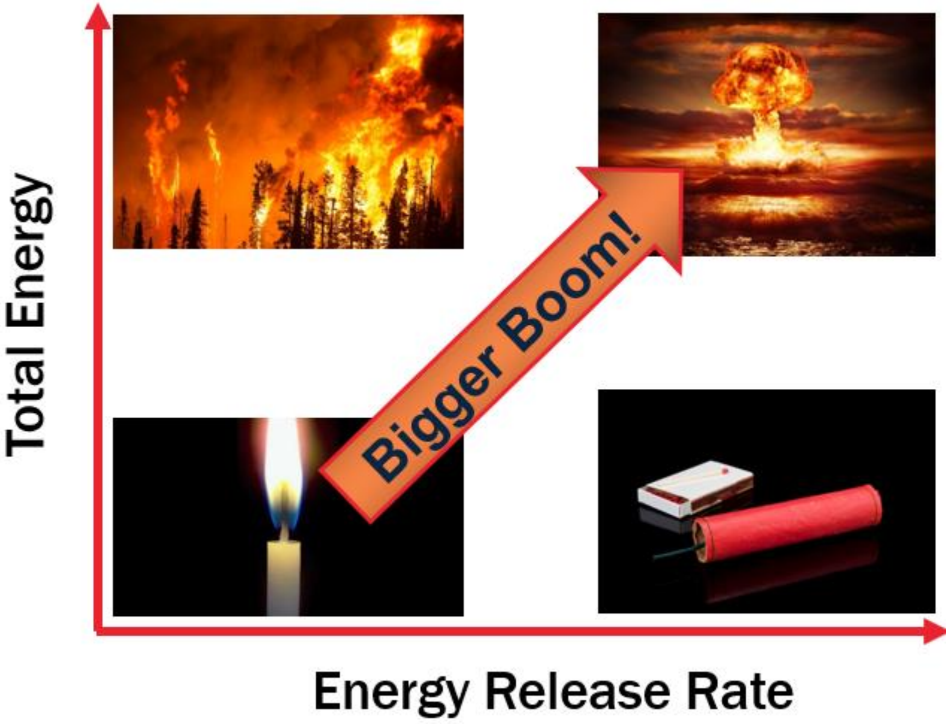

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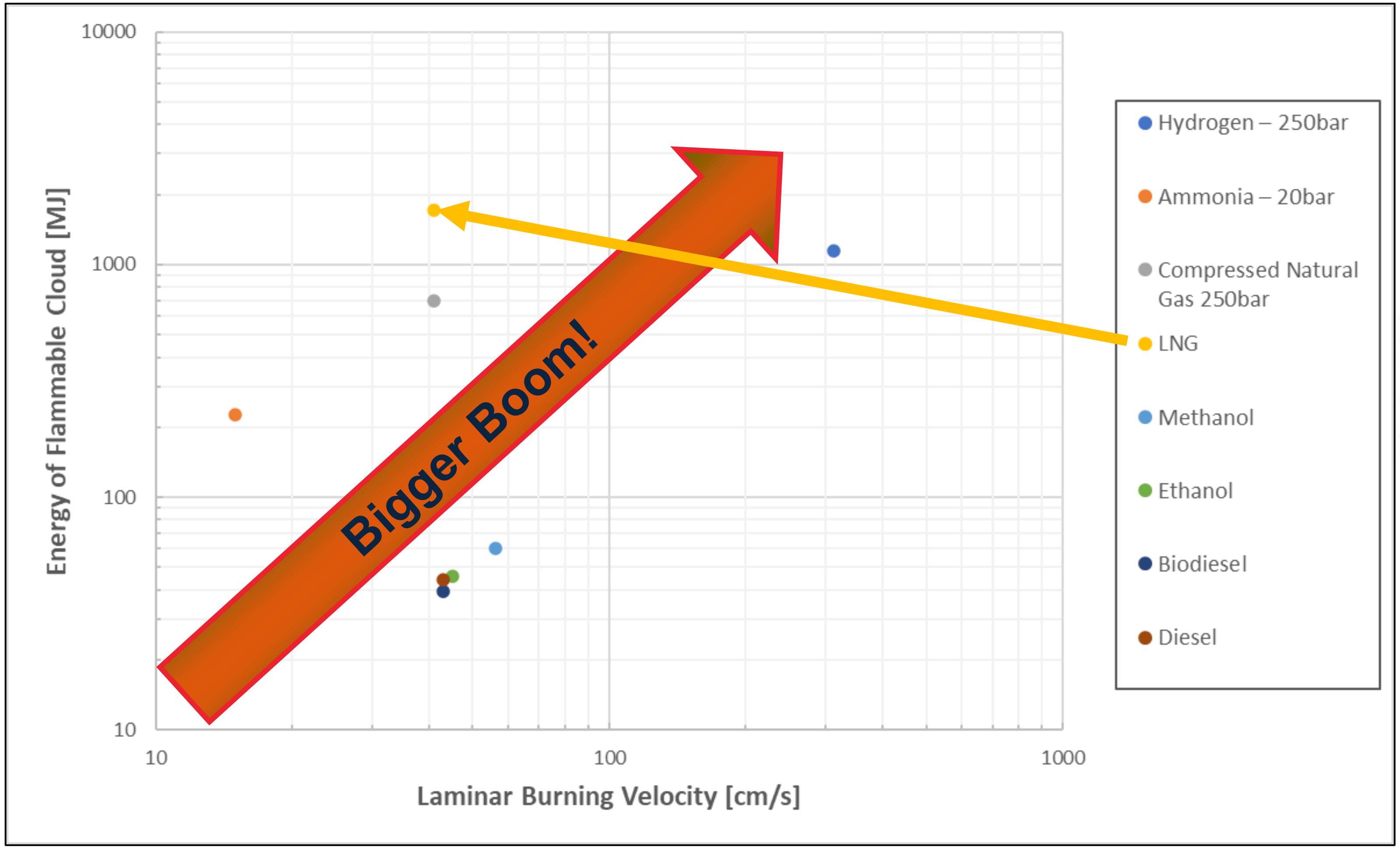

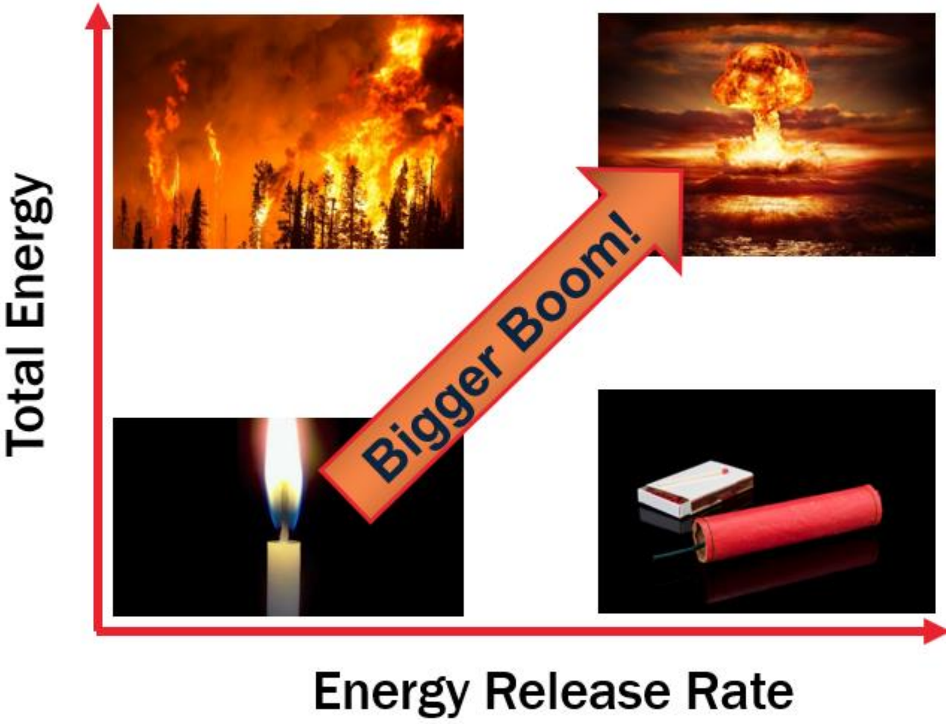

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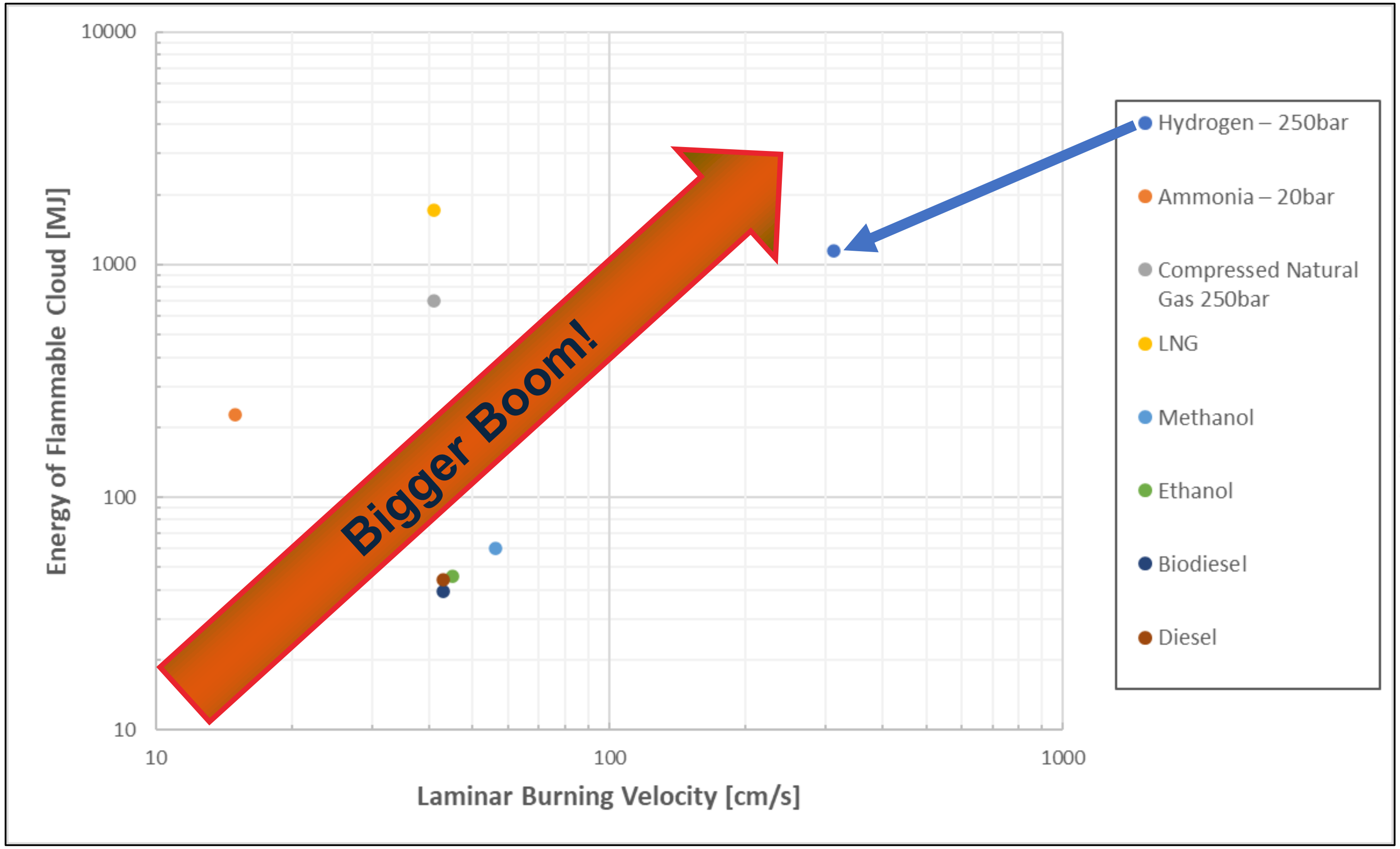
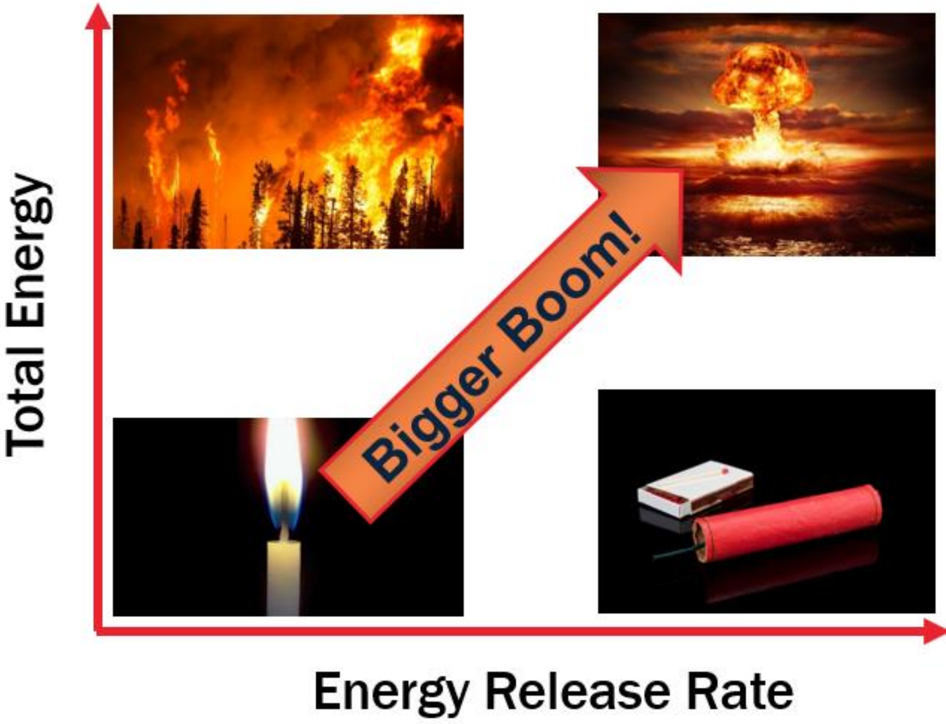




Relevant BakerRisk Research

2010

DDT in a Lean Hydrogen-Air Unconfined VCE

2014

Are Hydrogen UVCEs Credible?

2017

Hydrogen Jet VCE: A Model for Predicting Blast Size and Application to Risk Assessment

2017

Ammonia and Hydrogen VCE Testing

2018

Vented Hydrogen DDTs

2020/21

Hydrogen Ignition Testing

Current Status Marker

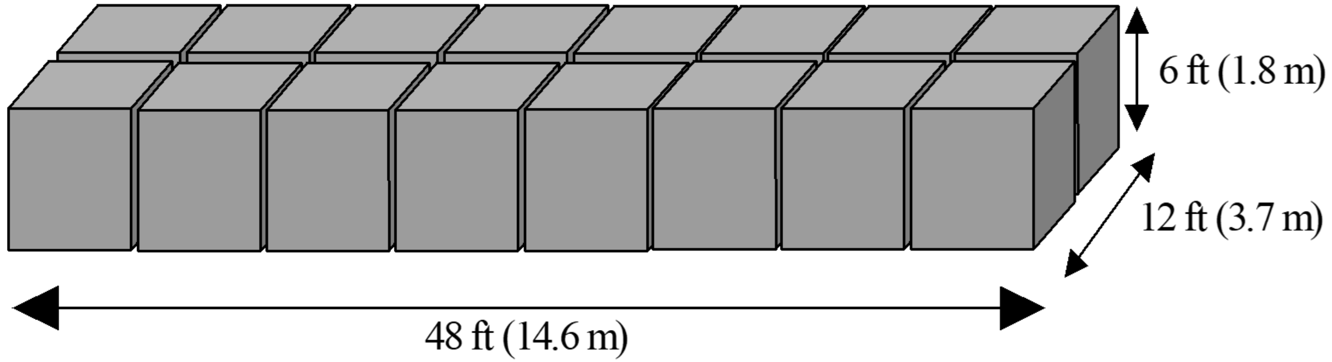
Future work:

Detonation Wave Failure Criteria

Design Constraints for Hydrogen Deflagrations

Hydrogen Testing Approach

- The congestion array was made up of a regular array of vertical circular tubes:
  - Diameter: 2.375-in (60mm)
  - Area Blockage: 22%
  - Volume Blockage: 4.1%



Schematic of Hydrogen Test Rig

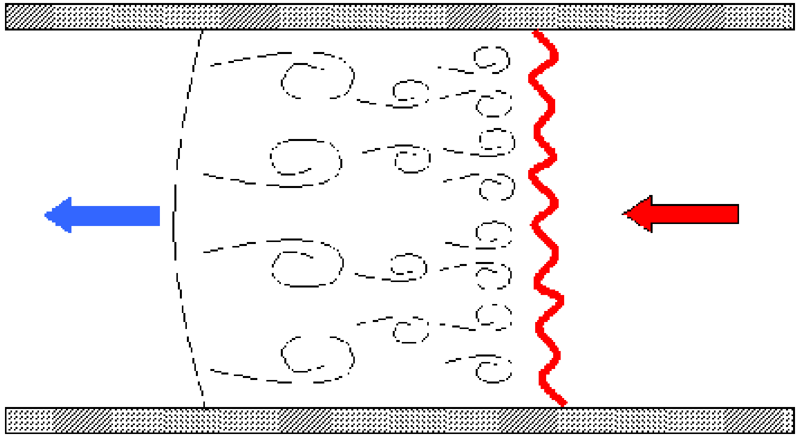
Photograph of Hydrogen Test Rig

18% Hydrogen HD Video

20% Hydrogen HD Video

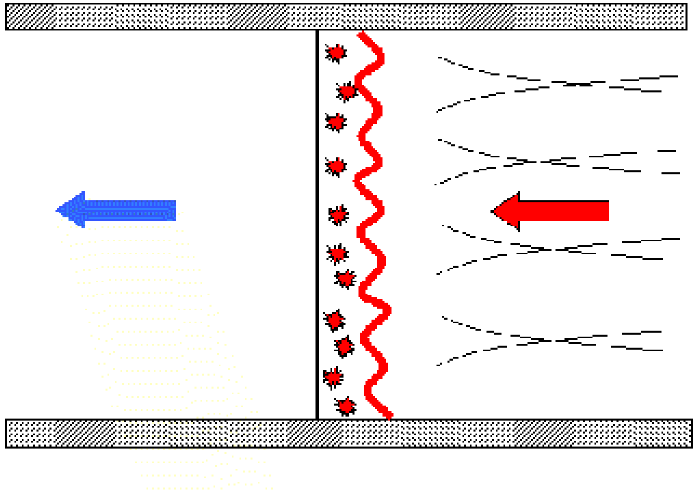
22% Hydrogen HD Video

Deflagrations and Detonations



Deflagration

Detonation



Detonations

Detonations can result from:

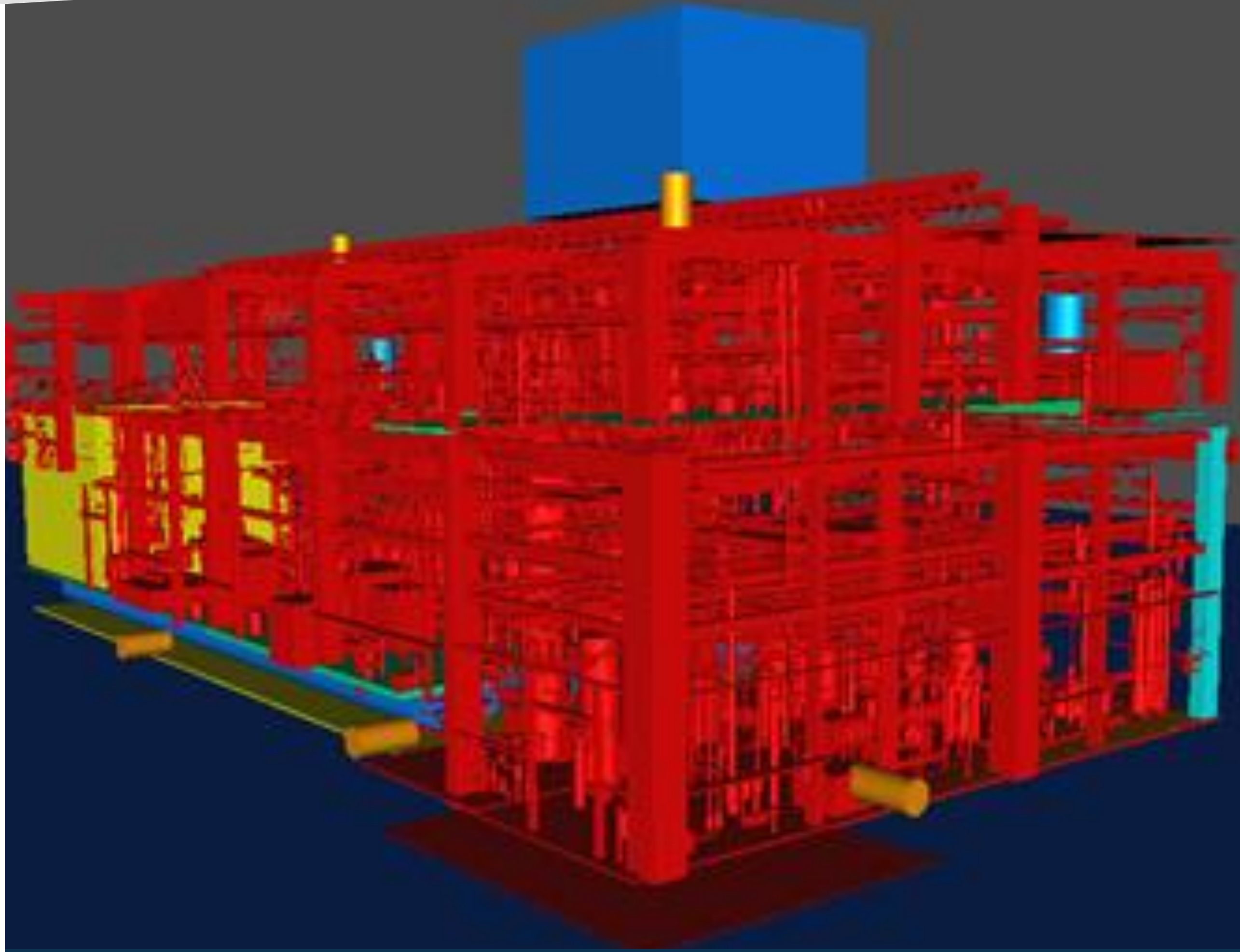
- Direct initiation
  - Very high energy initiation source required (e.g., high explosives)
  - Not normally a consideration for accidental VCEs
- Deflagration-to-detonation transition (DDT)
  - Flame accelerates to a high flame speed and undergoes a DDT
  - Can be of concern for accidental VCEs, particularly for high reactivity fuels, large flame travel distances and/or high levels of congestion

DDTs will propagate into the unconguested portion of the cloud

- Increases available explosion energy and safe stand-off distance from the explosion source to the target

Why Do We Care? (1 of 2)

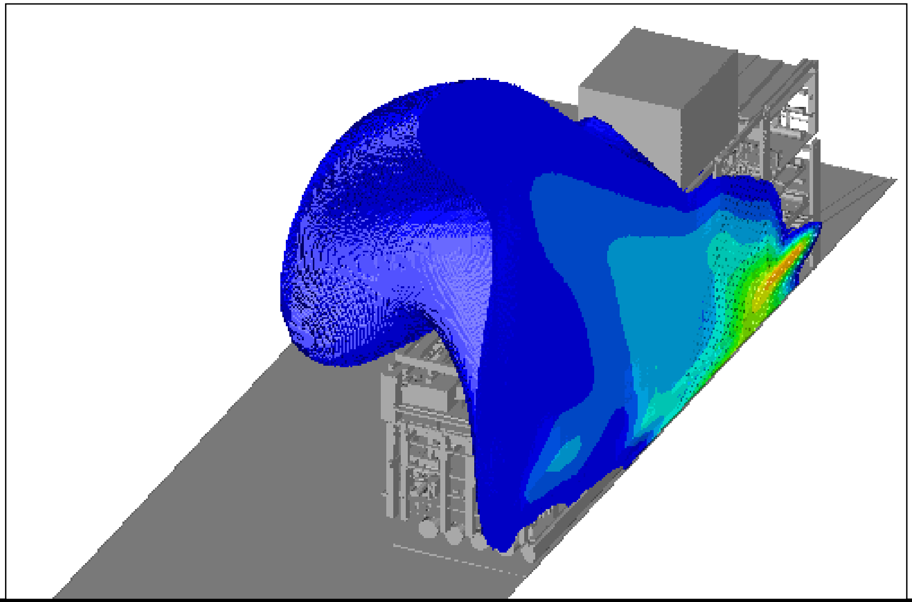
- Buoyancy does not exert significant influence until dispersing mixture has slowed sufficiently for momentum forces to weaken.
- A significant portion of a hydrogen cloud can extend beyond the congested region of a facility.
- Consider the following release & conditions:
  - 2-inch (5 cm) hole size
  - 1,400 psig (97 bar) at 550 °F (288 °C)
  - Gives release rate of 8.4 kg/s

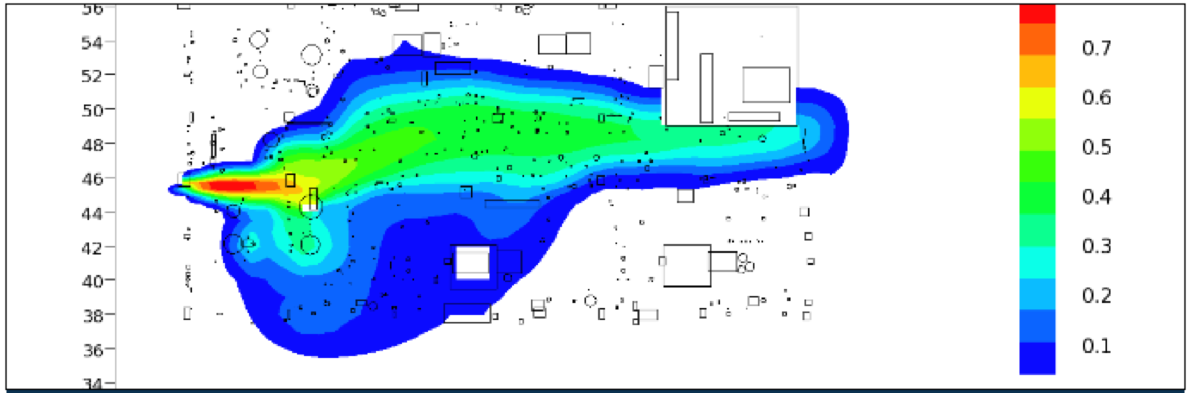


Congested Module - 37 m x 19 m x 12 m (8,120 m^3)

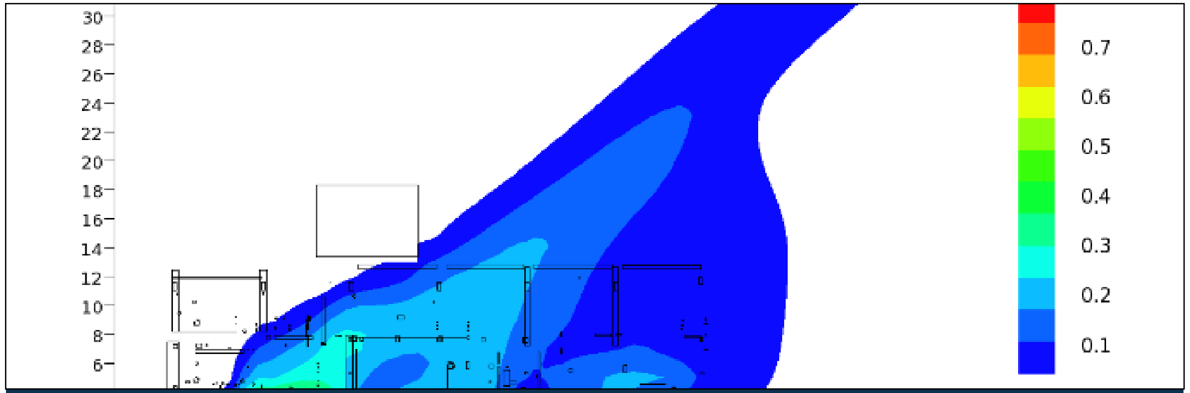
Why do We Care? (2 of 2)

- Flammable gas contours (8 kg/s)
  - Molar concentrations from LFL (4%) to 80% H_2
- Total flammable cloud volume is roughly 3 to 7 times that within the module
  - Important for DDT, as detonation wave can propagate into flammable cloud outside module





Plan View



Elevation View

Key Takeaways: Hydrogen

1 **Hydrogen is highly reactive**

Laminar burning velocity is 5 to 8 × higher than a typical hydrocarbon

2 **Hydrogen Releases can be Momentum Driven**

High pressure releases do not “float away” until momentum forces have been overcome

3 **Hydrogen can undergo a DDT**

Lean hydrogen-air mixtures have been shown to DDT

4 **DDTs are more hazardous than Deflagrations**

Detonations increase the explosion energy and can decrease stand-off distance

Relevant BakerRisk Research

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DDT in a Lean Hydrogen-Air Unconfined VCE

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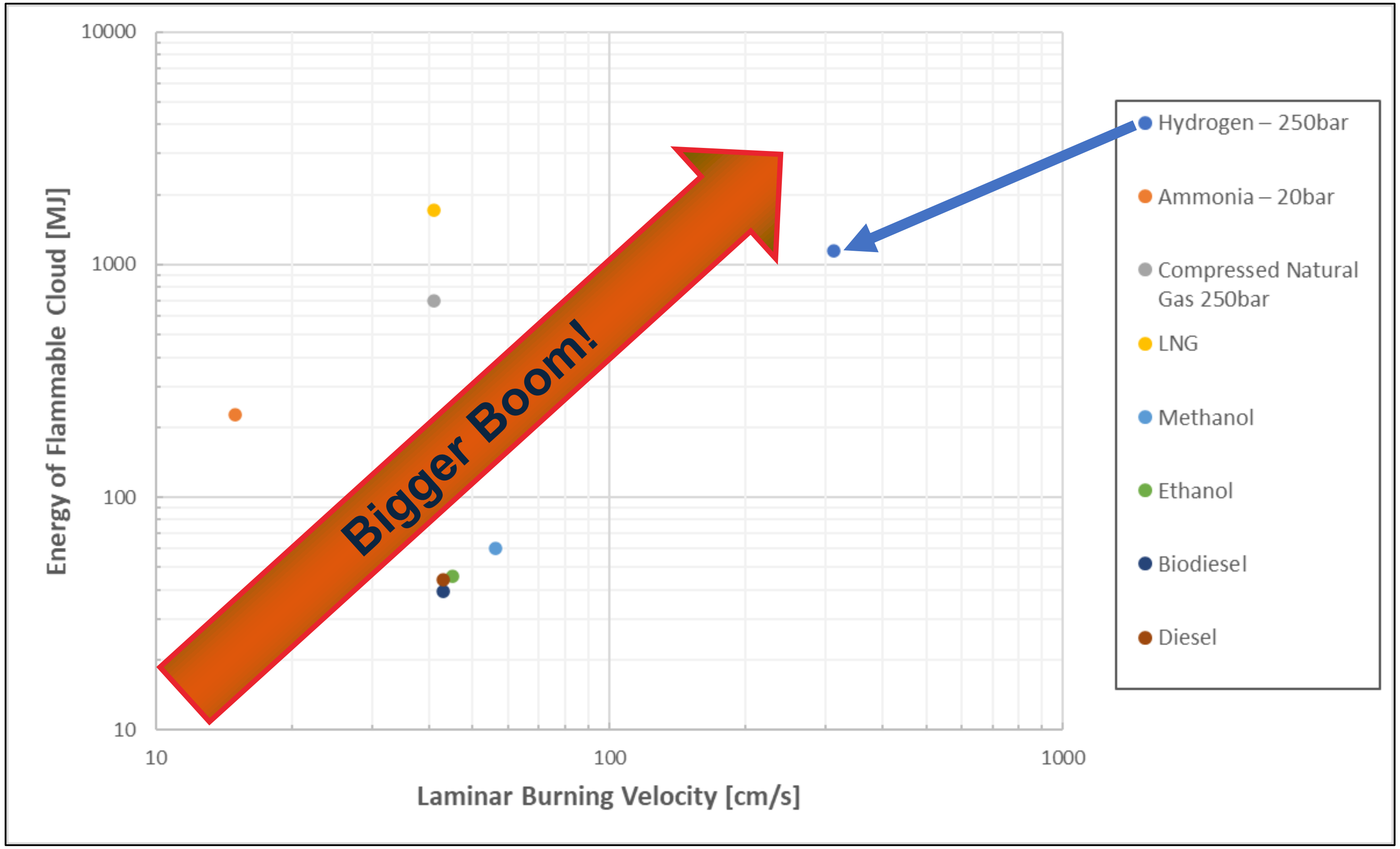

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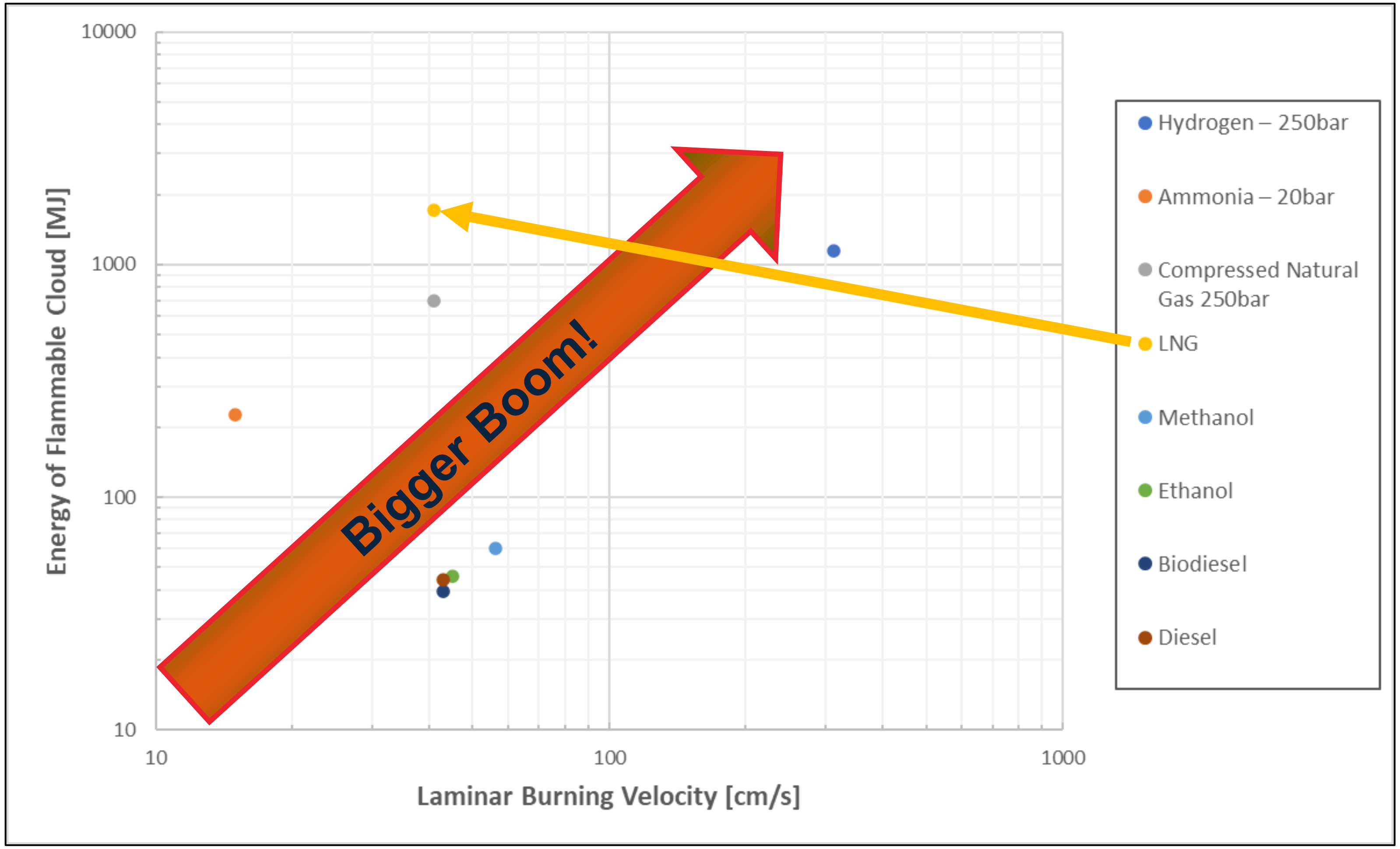

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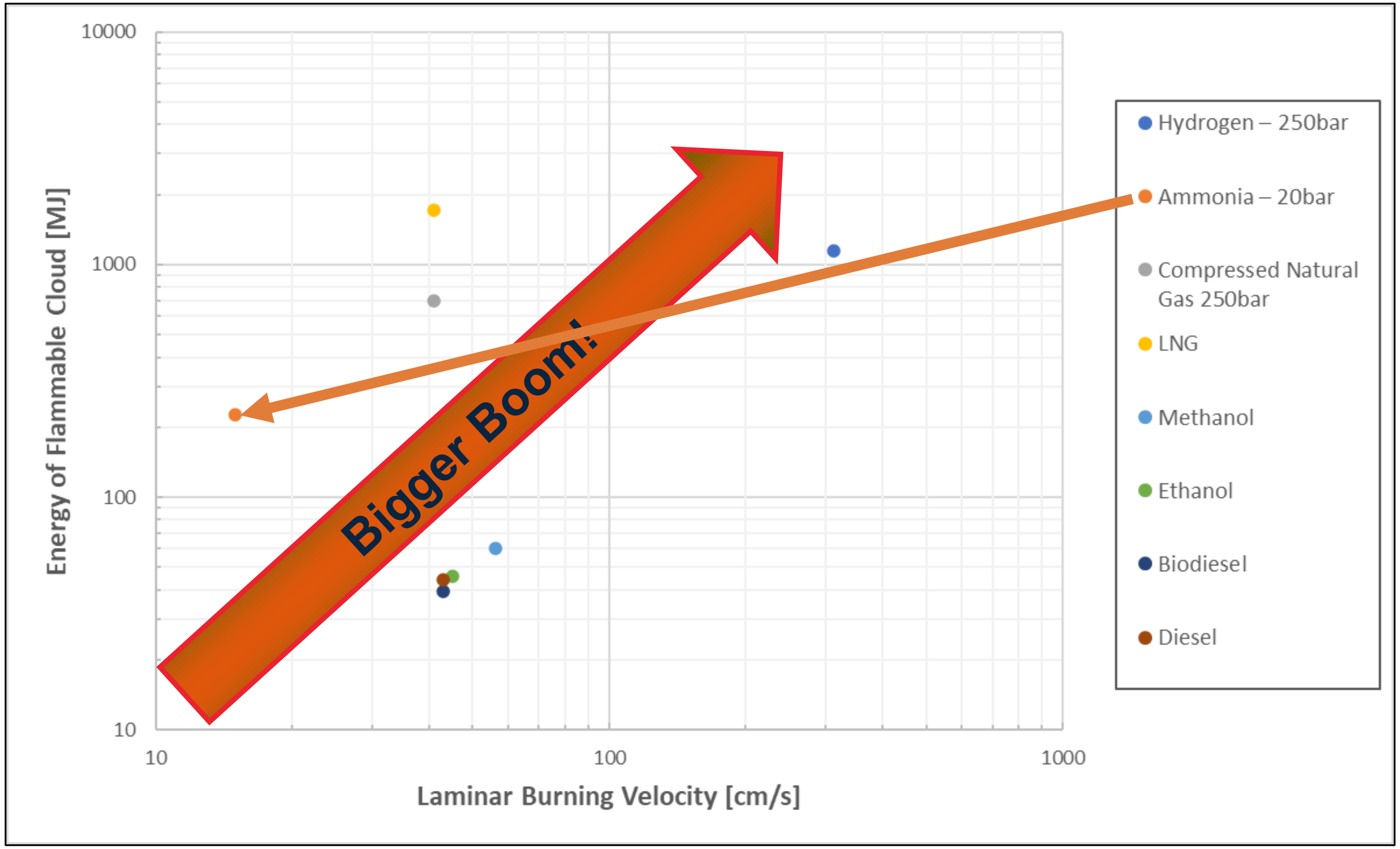


Ammonia / Methane Testing Approach

Acceptable Fuel Concentration Band	Methane [vol.% (ER)]	Ammonia [vol.% (ER)]
Target Fuel Concentration (Peak LBV)	10.0 (1.05)	23.2 (1.15)

Methane HD Video

Methane HS Video

Ammonia HD Video

Ammonia/Methane Discussion of Results

- Methane-Air Tests
  - Maximum overpressure approximately 2 psig
  - Maximum flame speed approximately 500 ft/s (Mach 0.44)
- Ammonia-Air Tests
  - No recordable overpressures
  - Maximum flame speed approximately 25 ft/s (Mach 0.02)
- Created new "Very Low Reactivity" BST flame speed class based on the ratio of the observed methane-air and ammonia-air flame speeds, along with the existing low reactivity (methane) flame speed values

Key Takeaways: Ammonia

1 **Ammonia is a very low reactivity fuel**

30× lower laminar burning velocity (LBV) than hydrogen

2 **Ammonia will burn**

Ammonia's flammable limits and MIE are higher than most fuels, but it can form flammable clouds and ignite

3 **Unconfined NH_3 VCEs are more like flash fires**

Even in highly congested environments, ammonia-air clouds do not produce damaging last loads.
Enclosed (confined) ammonia releases can produce damaging blast loads.

4 **Primary NH_3 Hazard is Toxicity**

Don't forget toxic impacts are far reaching!

Hazard Comparison

- **Hazards associated with Hydrogen and Ammonia are different!**
- **It is not "fair" to compare them on a single hazard basis**
  - **Toxicity – Ammonia**
  - **Fire/Explosion – Hydrogen**
- **Risk analyses should consider site specific population(s), storage conditions, and operations**

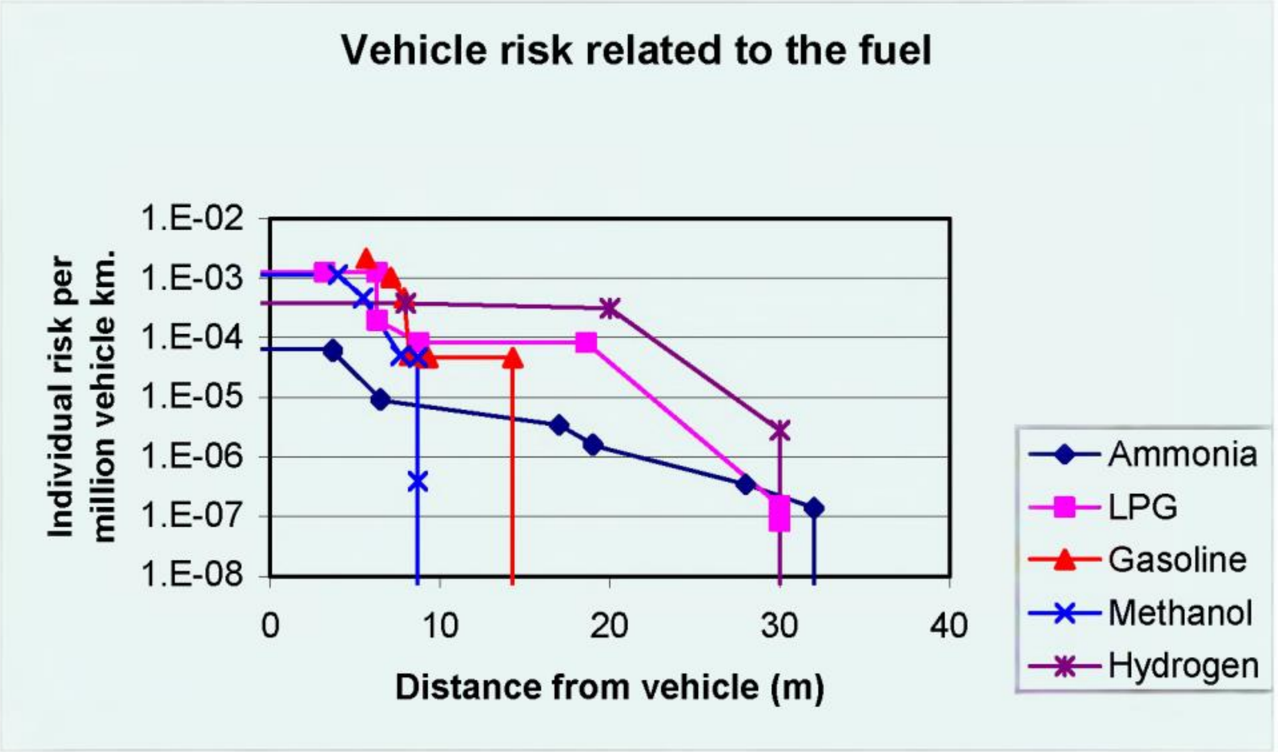


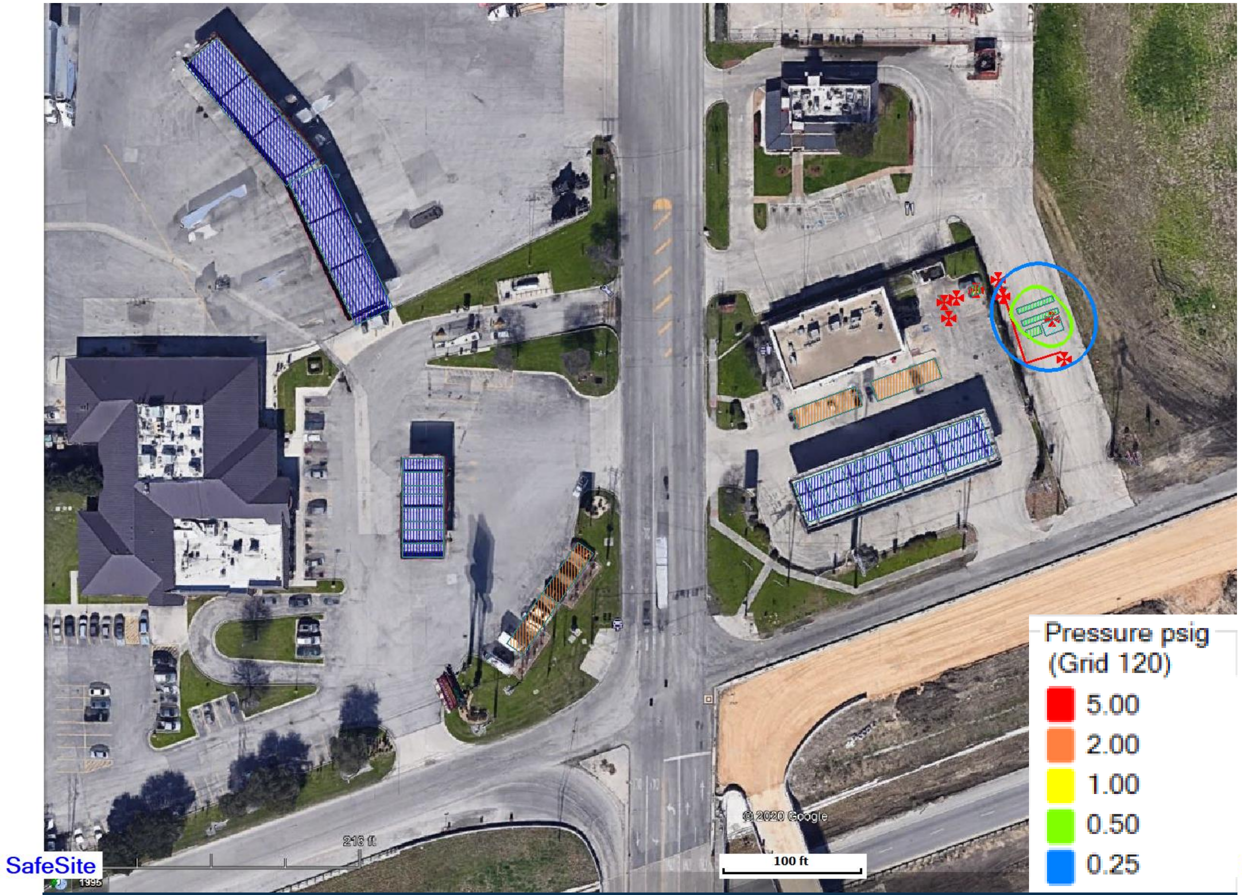
Figure 10 Comparison of individual risk as function of distance to a vehicle

Safety Assessment of Ammonia as a Transport Fuel
Riso-R-1504(EN)

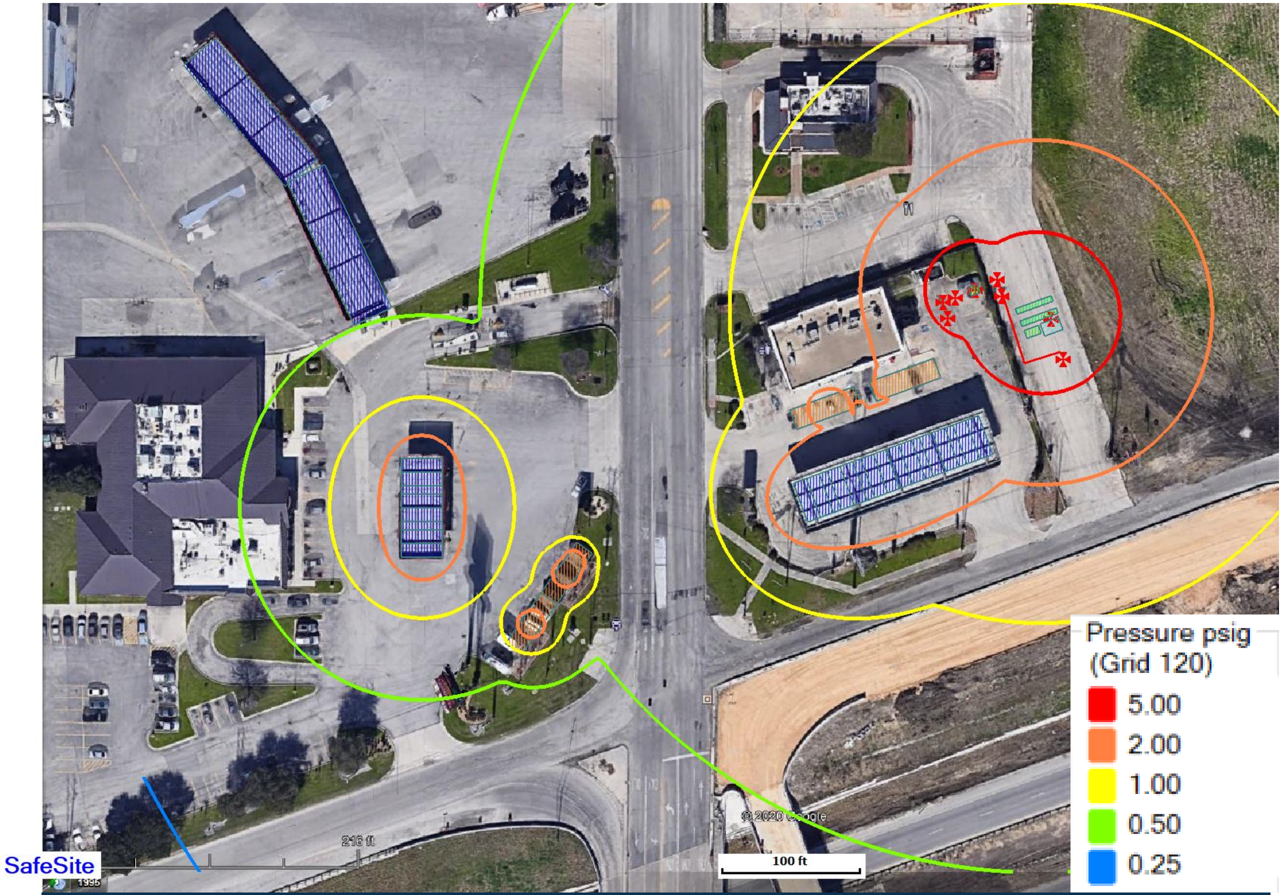
Site Specific Hazard Analysis

- Site specific analysis is facilitated by several commercially available software suites
  - BakerRisk's SafeSite©,
  - DNV's Safeti,
  - Gexcon's Shell FRED
- Codes facilitate simplified dispersion, blast, fire, and toxic model development
- Commercial CFD codes can also be used for this purpose
- Contours on the following slide were developed for a fictious retrofit of an existing fueling station in South Texas for alternative fuels (LNH_3, LNG, LH_2)
  - No overpressure contours were predicted for the ammonia scenario

Overpressure Contours



2-inch LNG Release (-260 F, 3 psig)



2-inch LH_2 Release (-408 F, 90 psig)

Key Takeaways

1 Apparent Low/No-Carbon Mandate

Energy density, infrastructure, and logistical challenges are being addressed.

2 Hydrogen, LNG and Ammonia are Options

LH_2 and NH_3 appear to be the preferred "Carbon-Free" energy carriers.

3 All Fuels Have Unique Hazards

NH_3 (toxicity) and CH_4 and H_2 (fire/explosion). All hazards need to be considered.

4 Proper Siting is Critical

Safety incidents have impacted the industry (Nel/Uno-X, Gangneung, S Korea).

A major safety incident could prevent full development of this technology (e.g., 3 Mile Island).

For More Information

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Chester, CH4 9QR

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+44 (0) 7595 395000

RMagraw@BakerRisk.com