Hazards31

Ammonia, Methane & Hydrogen, Oh My!

Understanding Hazards from Alternative Power to Gas Options

Darren Malik, P.E., CFEI

Hazards 31
Nov. 2021

Introduction

- Darren R. Malik, P.E., CFEI
  - Graduate of Texas A&M University
    - B.S. Nuclear Engineering, 2008
      - Nuclear Renaissance, Hydrogen Economy
    - M.S. Mechanical Engineering, 2010
      - Thermal Energy Storage for Concentrating Solar Power Plants (CSPP)
  - General Manager – Testing Operations, Baker Engineering and Risk Consultants, Inc.
    - Testing:
      - Research & Development, Product Verification, Incident Reconstruction/Scenario Validation
    - Facility Siting Studies
    - Incident Investigations
    - Combustible Dust Hazard Assessments

Hazards31

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

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

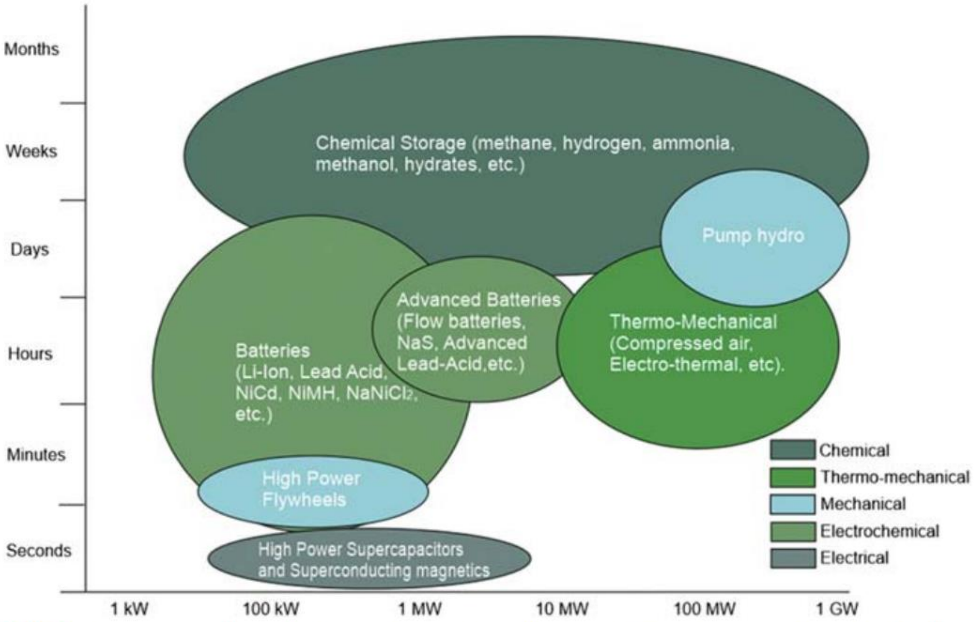
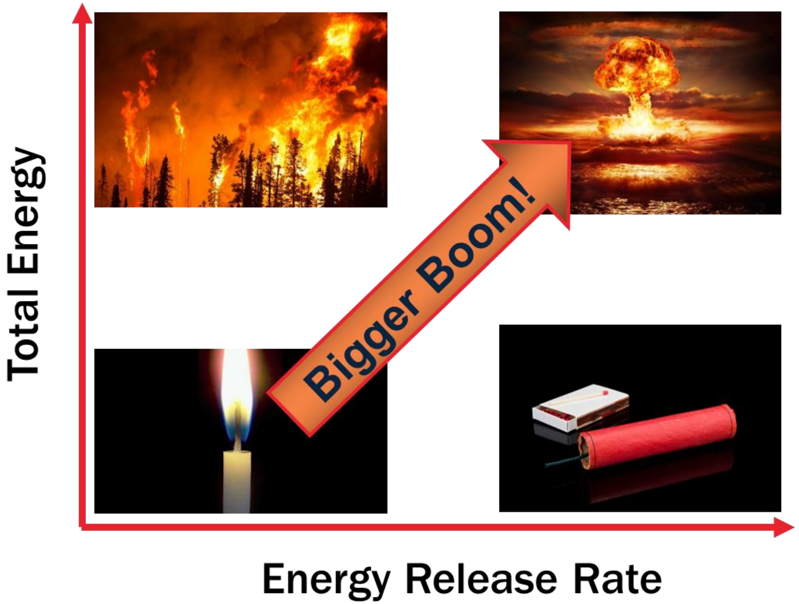


FIG. 1.6 Power versus time of storage. Comparison between different energy storage technologies.

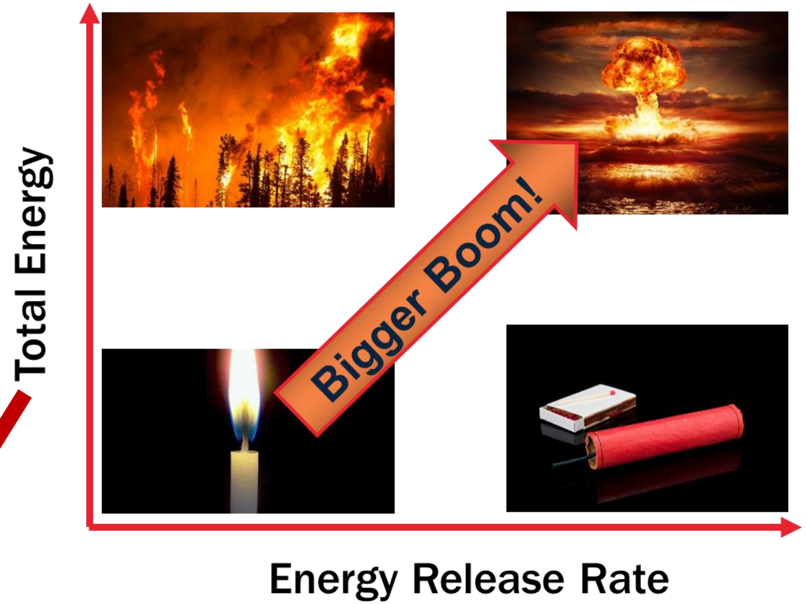
Fundamental Design Parameters

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/m^3]	2.9	3.1	2.6
Gravimetric Energy Density [MJ/kg]	23	54	142
Volumetric Energy Density [MJ/L]	14	22	10



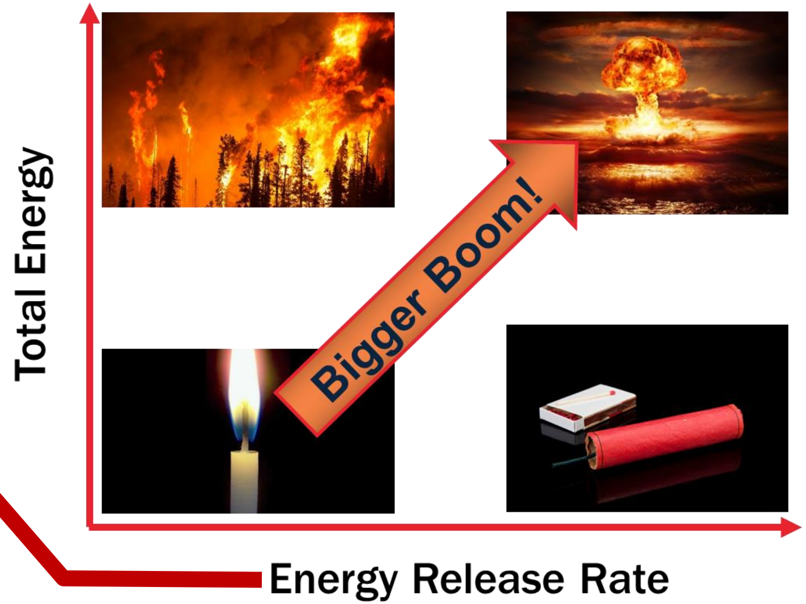
Fundamental Design Parameters

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/m^3]	2.9	3.1	2.6
Gravimetric Energy Density [MJ/kg]	23	54	142
Volumetric Energy Density [MJ/L]	14	22	10

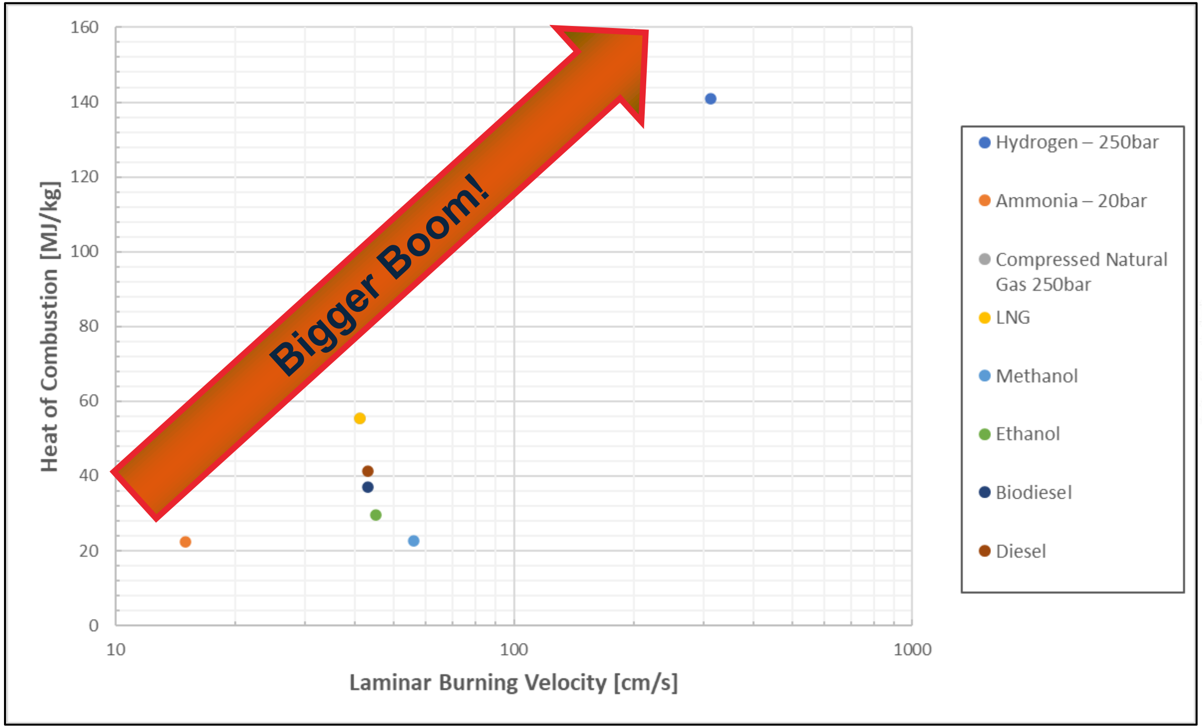


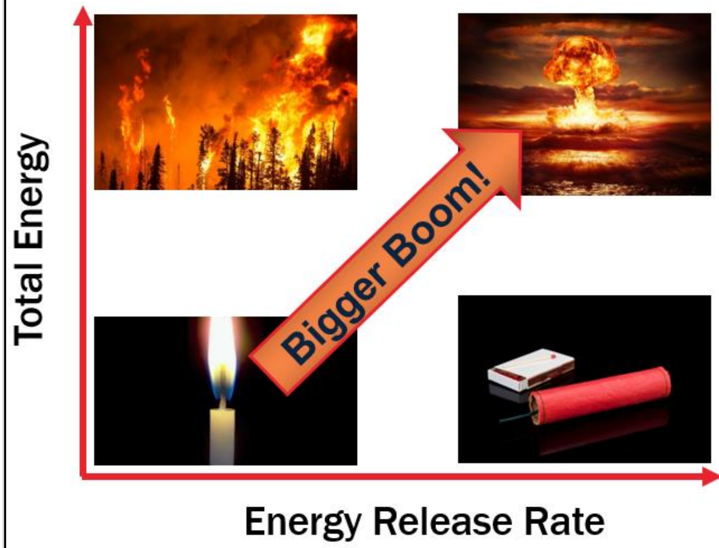
Fundamental Design Parameters

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/m^3]	2.9	3.1	2.6
Gravimetric Energy Density [MJ/kg]	23	54	142
Volumetric Energy Density [MJ/L]	14	22	10

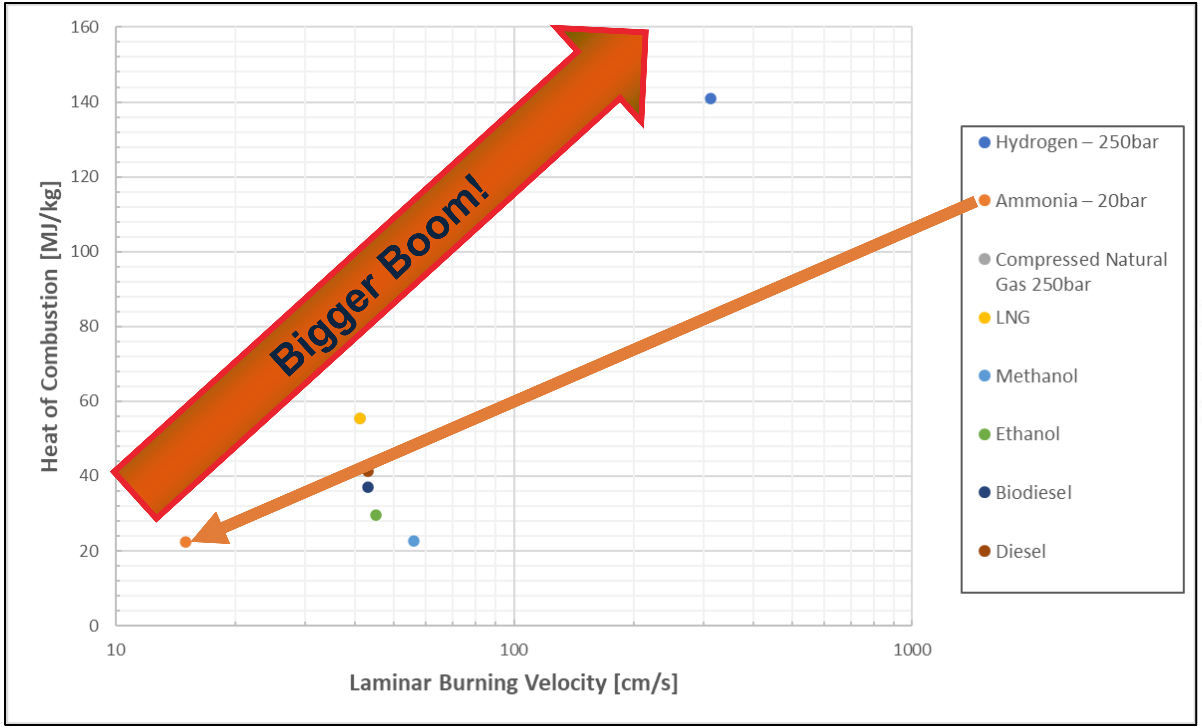


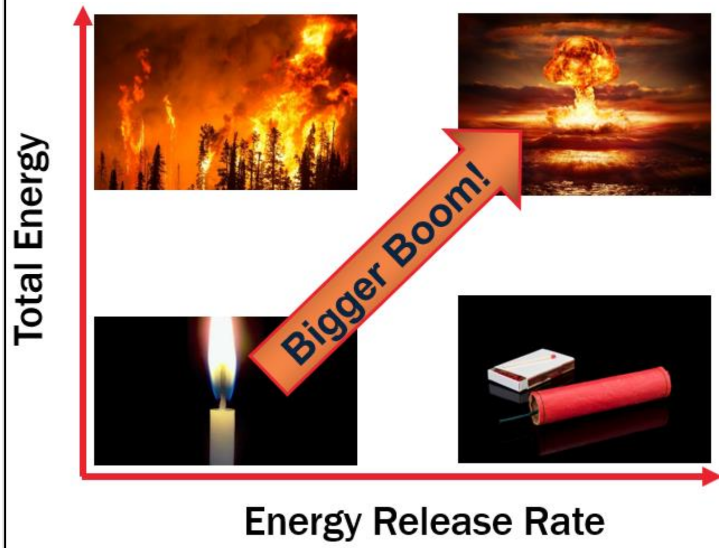
Heat of Combustion vs. Log Laminar Burning Velocity



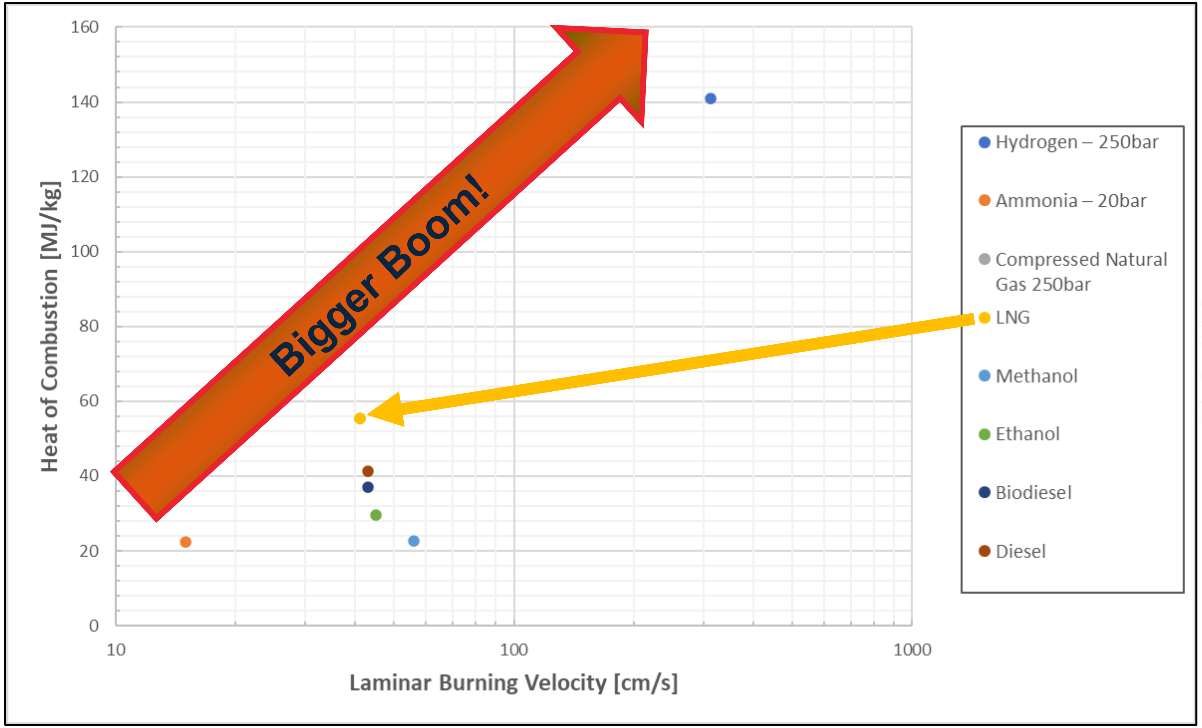


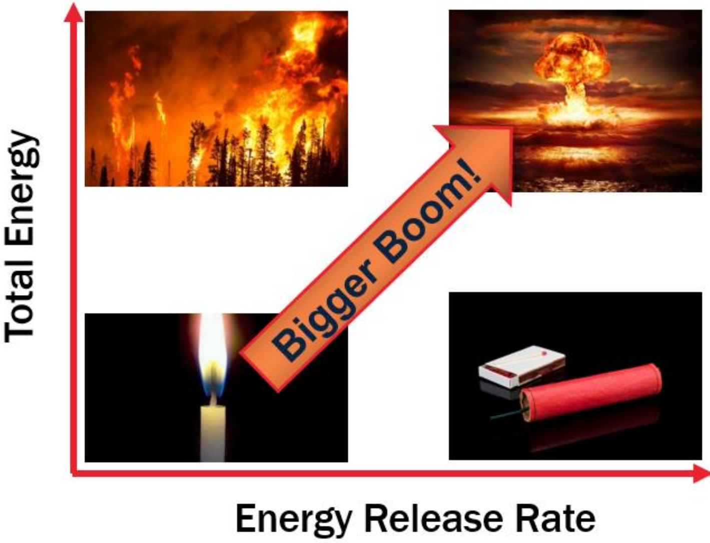
Heat of Combustion vs. Log Laminar Burning Velocity



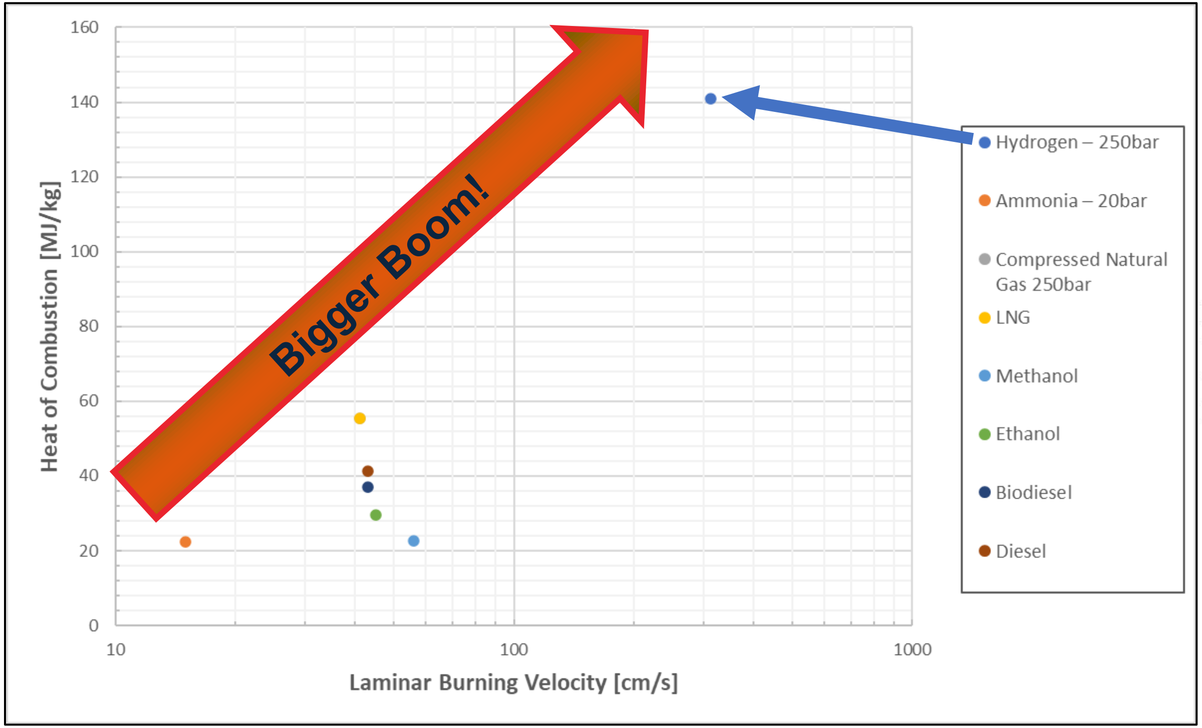


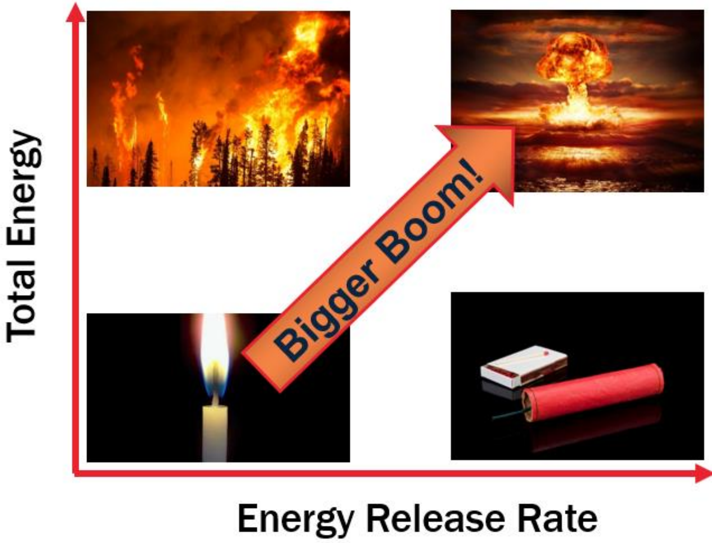
Heat of Combustion vs. Log Laminar Burning Velocity



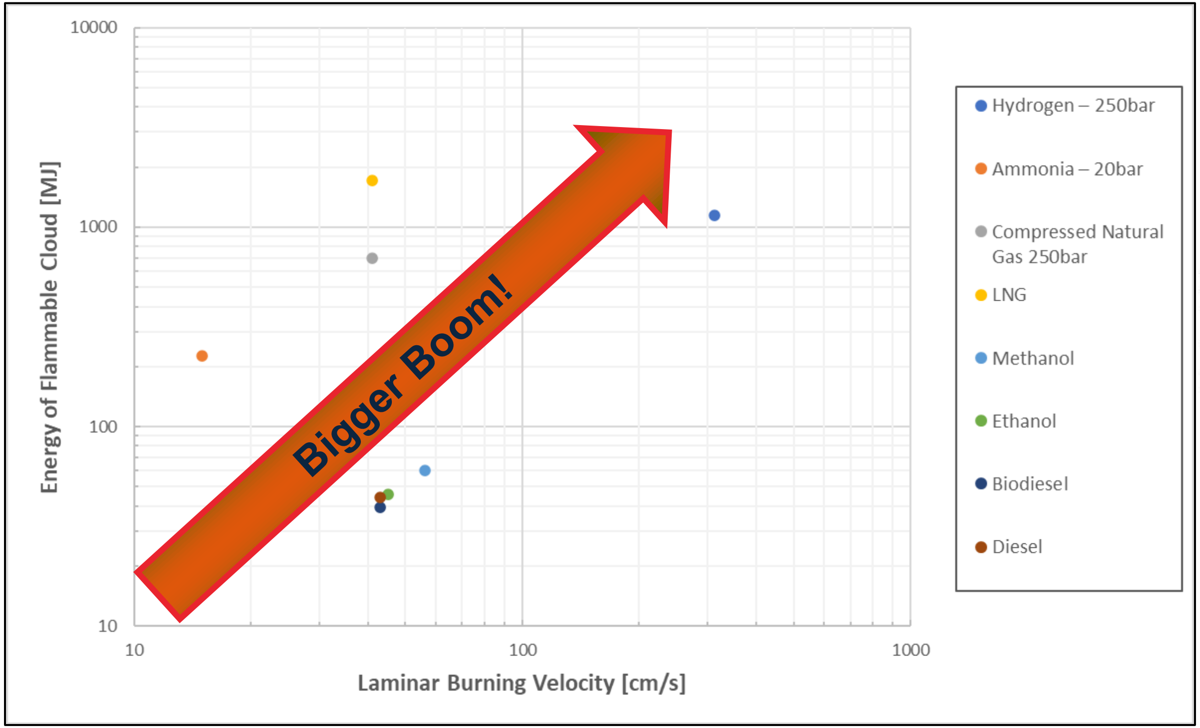


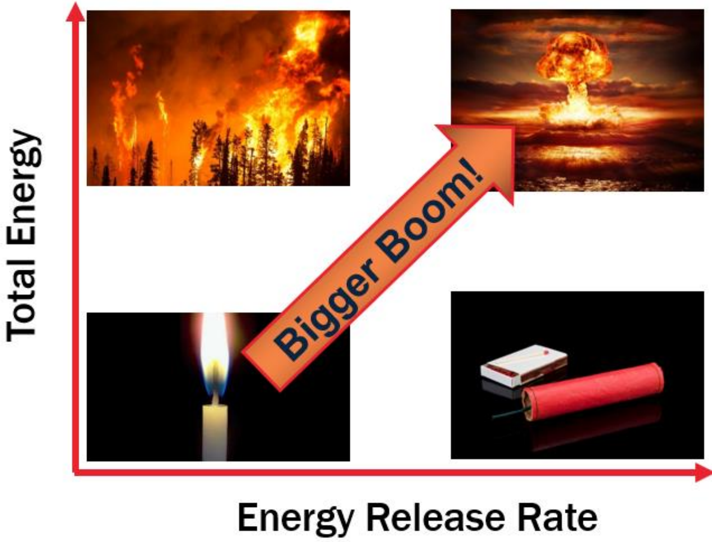
Heat of Combustion vs. Log Laminar Burning Velocity



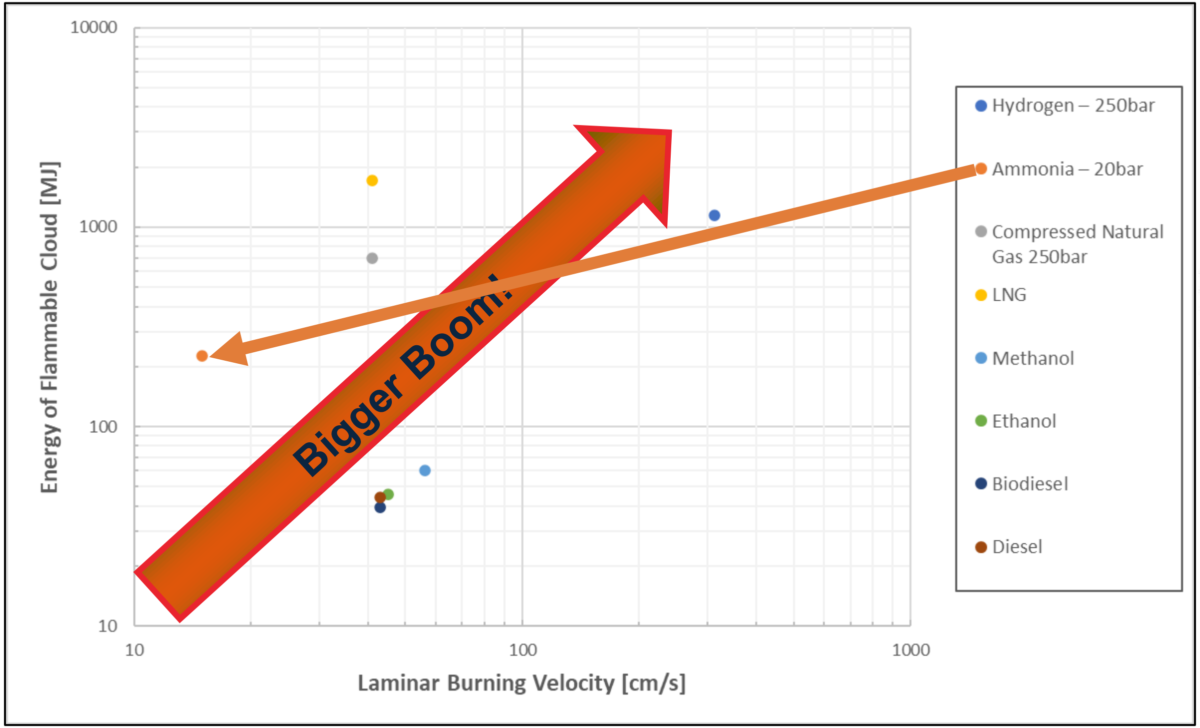


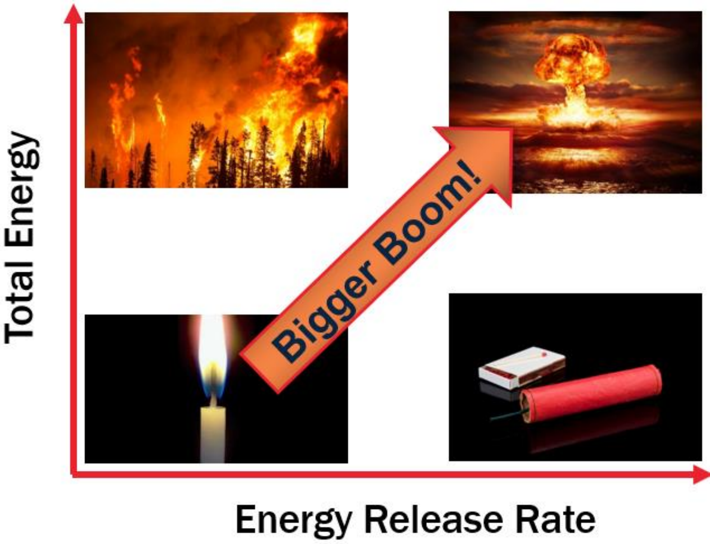
Predicted Flammable Cloud from 2-inch Release



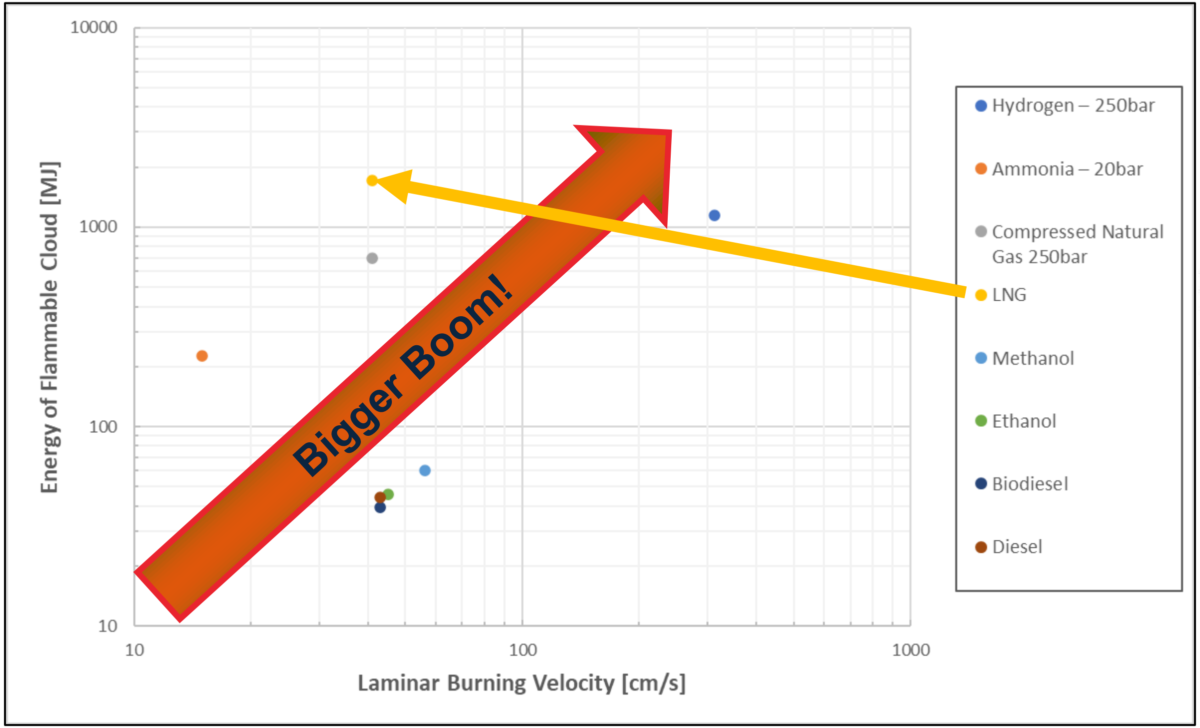


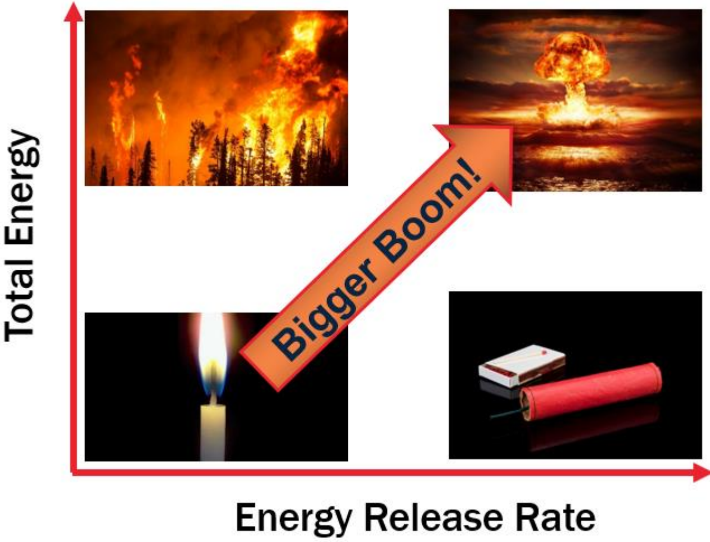
Predicted Flammable Cloud from 2-inch Release



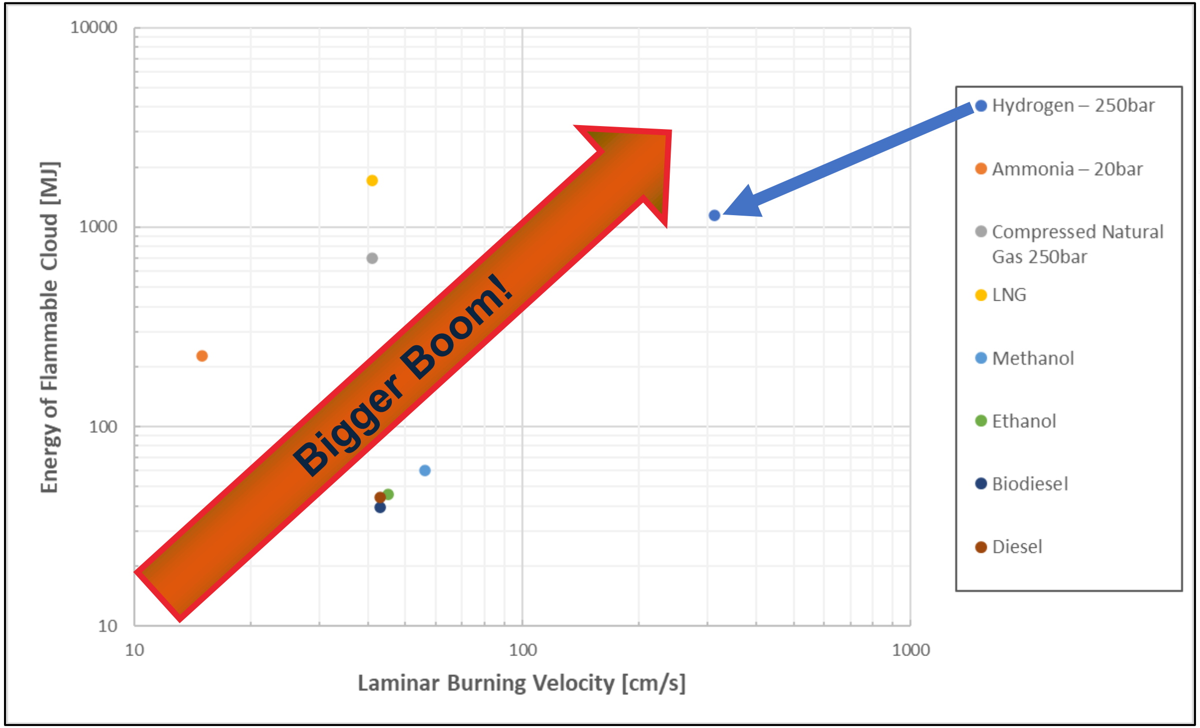


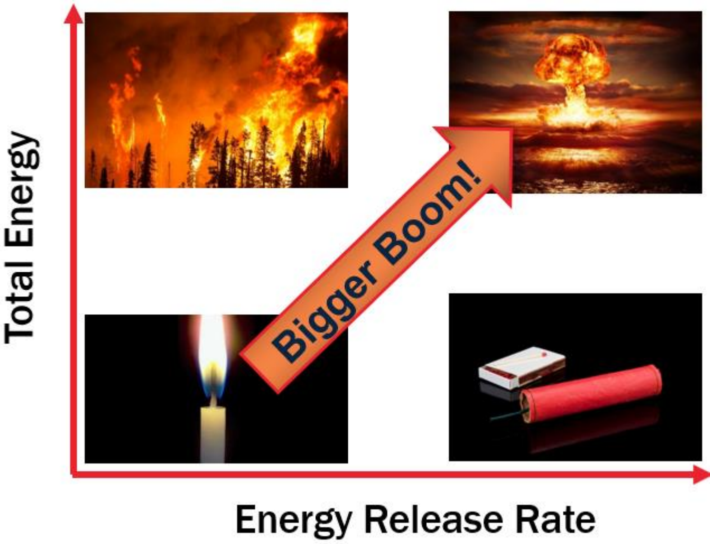
Predicted Flammable Cloud from 2-inch Release





Predicted Flammable Cloud from 2-inch Release





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

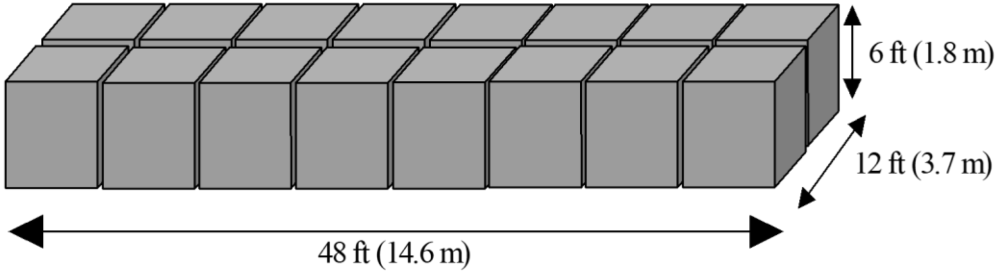
Current Status Marker

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

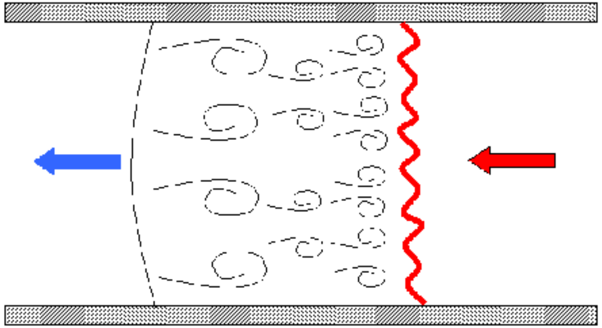
Photograph of Hydrogen Test Rig

18% Hydrogen HD Video

20% Hydrogen HD Video

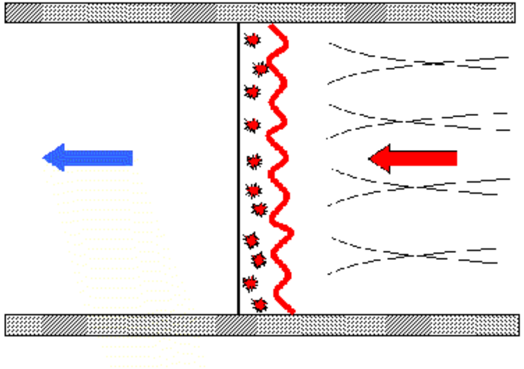
22% Hydrogen HD Video

Deflagrations and Detonations



Deflagration

Detonation



Detonations

Detonations can result from:

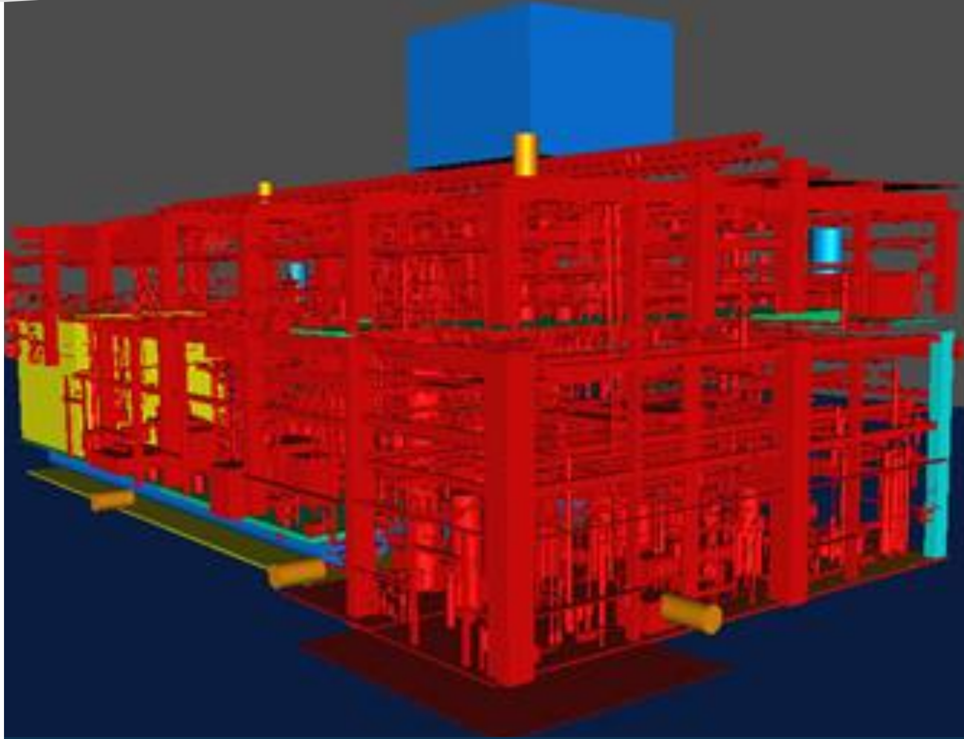
- Direct initiation
  - Very high energy initiation source required (e.g., high explosives)
  - Not normally a consideration for accidental VCEs
- Deflagration-to-detonation transition (DDT)
  - Flame accelerates to a high flame speed and undergoes a DDT
  - Can be of concern for accidental VCEs, particularly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

DDTs will propagate into the unconfined portion of the cloud

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

Why Do We Care? (1 of 2)

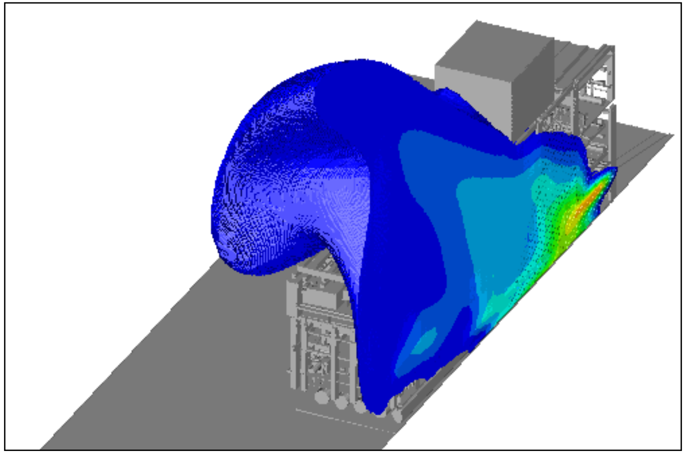
- Buoyancy does not exert significant influence until dispersing mixture has slowed sufficiently for momentum forces to weaken.
- A significant portion of a hydrogen cloud can extend beyond the congested region of a facility.
- Consider the following release & conditions:
  - 2-inch (5 cm) hole size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

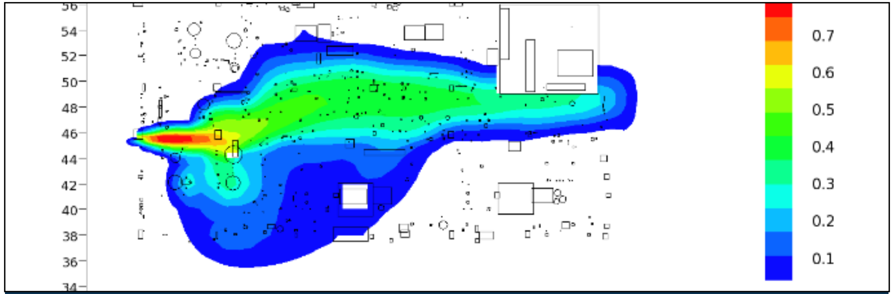


Congested Module - 37 m x 19 m x 12 m (8,120 m^3)

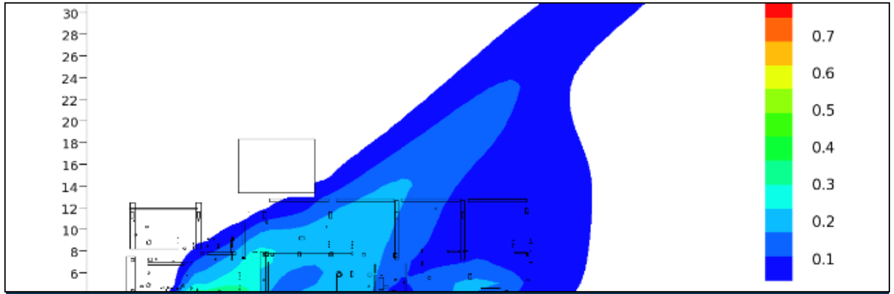
Why do We Care? (2 of 2)

- 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

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

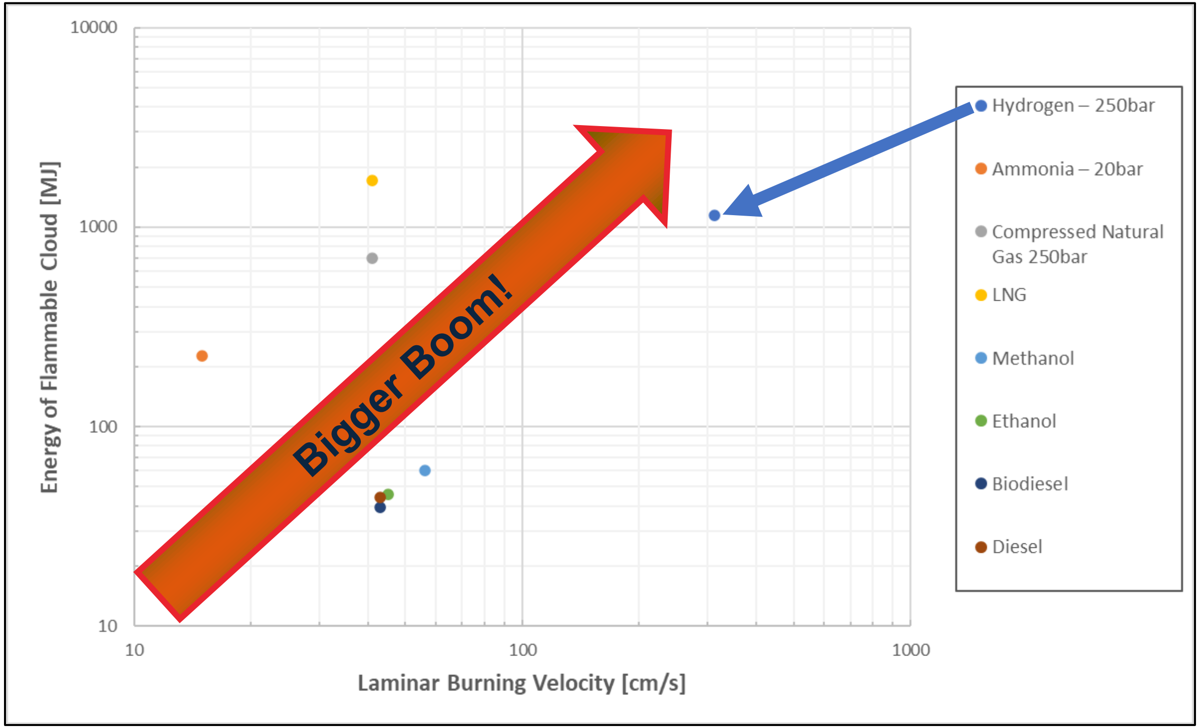
2020/21
Hydrogen Ignition Testing

Detonation Wave Failure Criteria

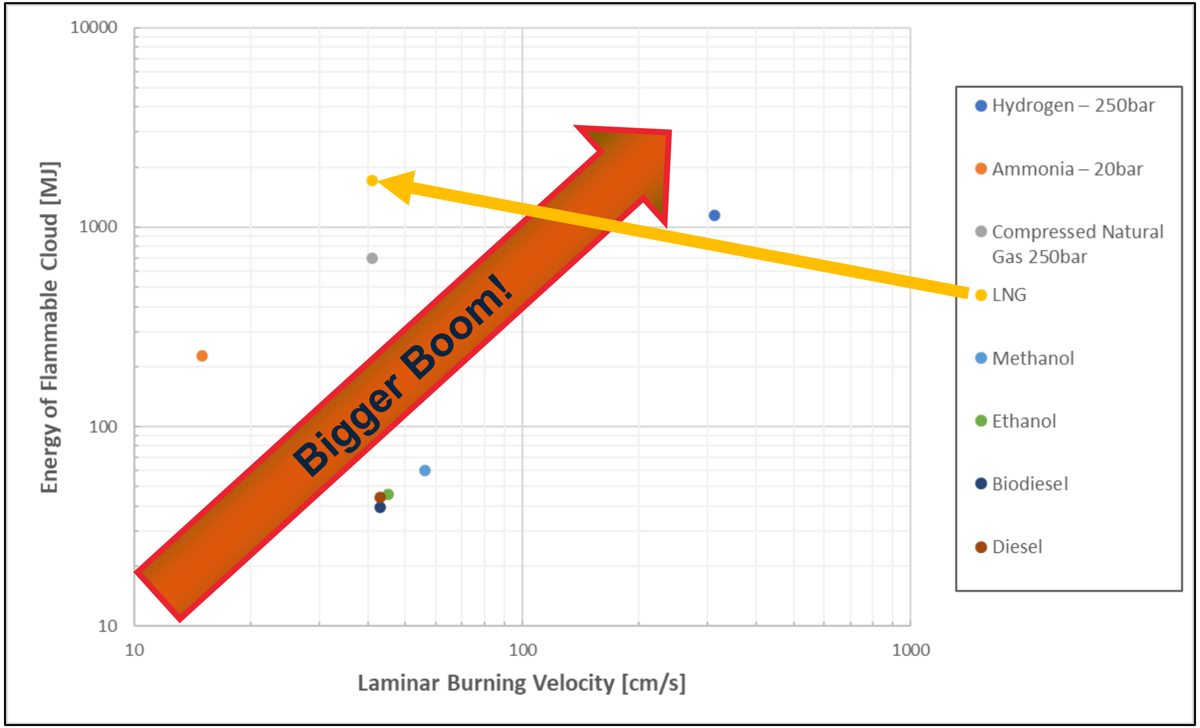
Design Constraints for Hydrogen Deflagrations

Current Status Marker

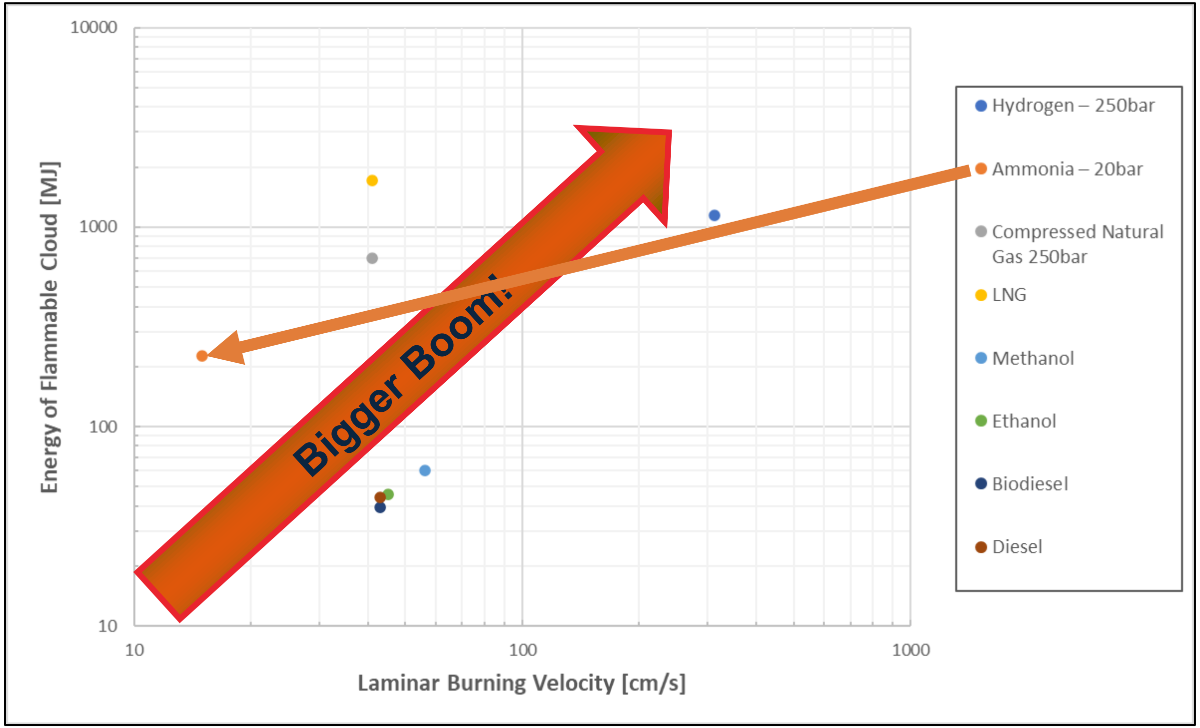
Predicted Flammable Cloud from 2-inch Release



Predicted Flammable Cloud from 2-inch Release



Predicted Flammable Cloud from 2-inch Release



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 (Borden Houston).

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**

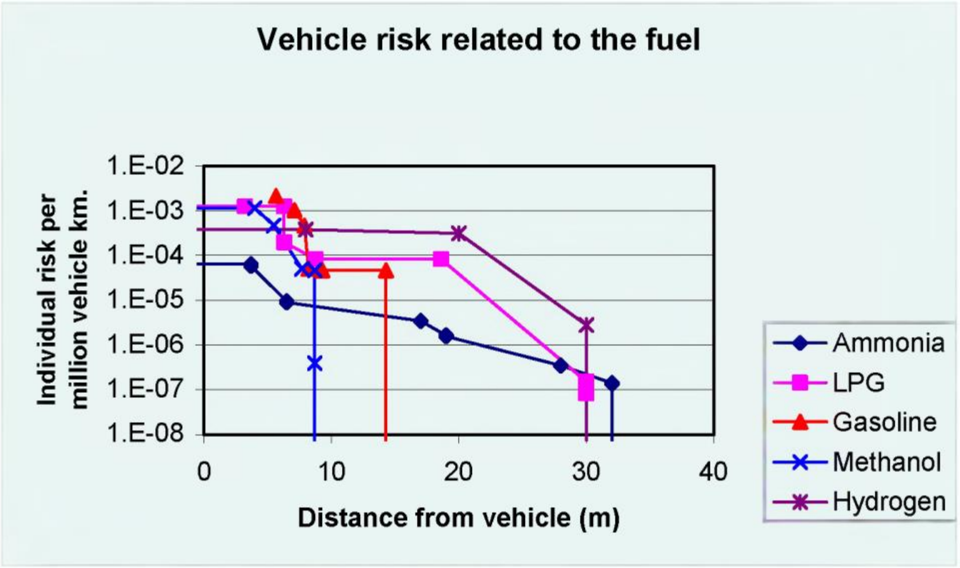


Figure 10 Comparison of individual risk as function of distance to a vehicle

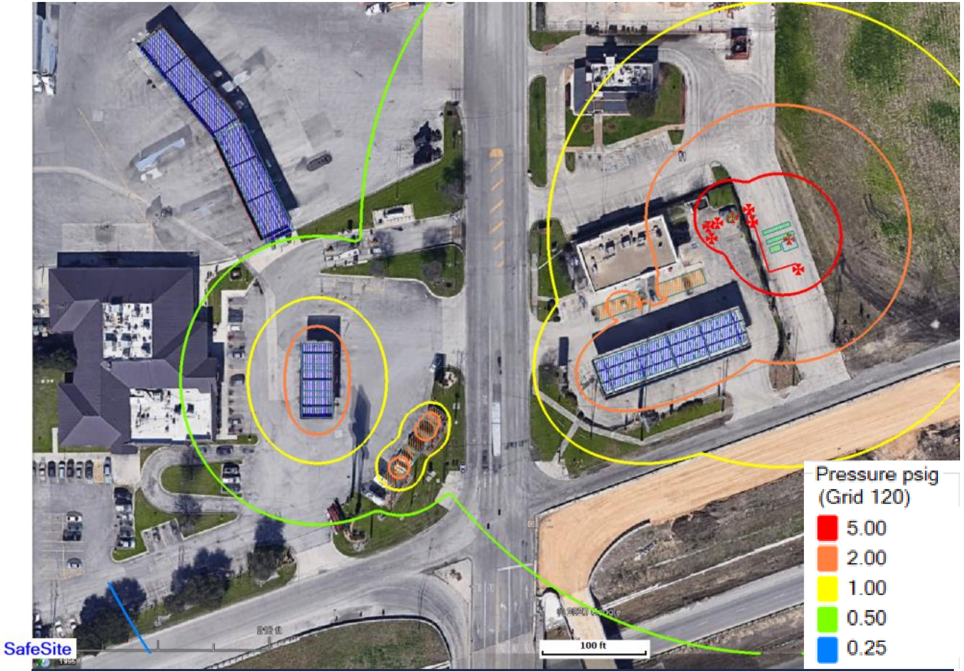
Safety Assessment of Ammonia as a Transport Fuel
Riso-R-1504(EN)

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

Darren Malik

BakerRisk
3330 Oakwell Court, Suite 100
San Antonio, TX 78218-3024

+1 (210) 824-5960

DMalik@BakerRisk.com