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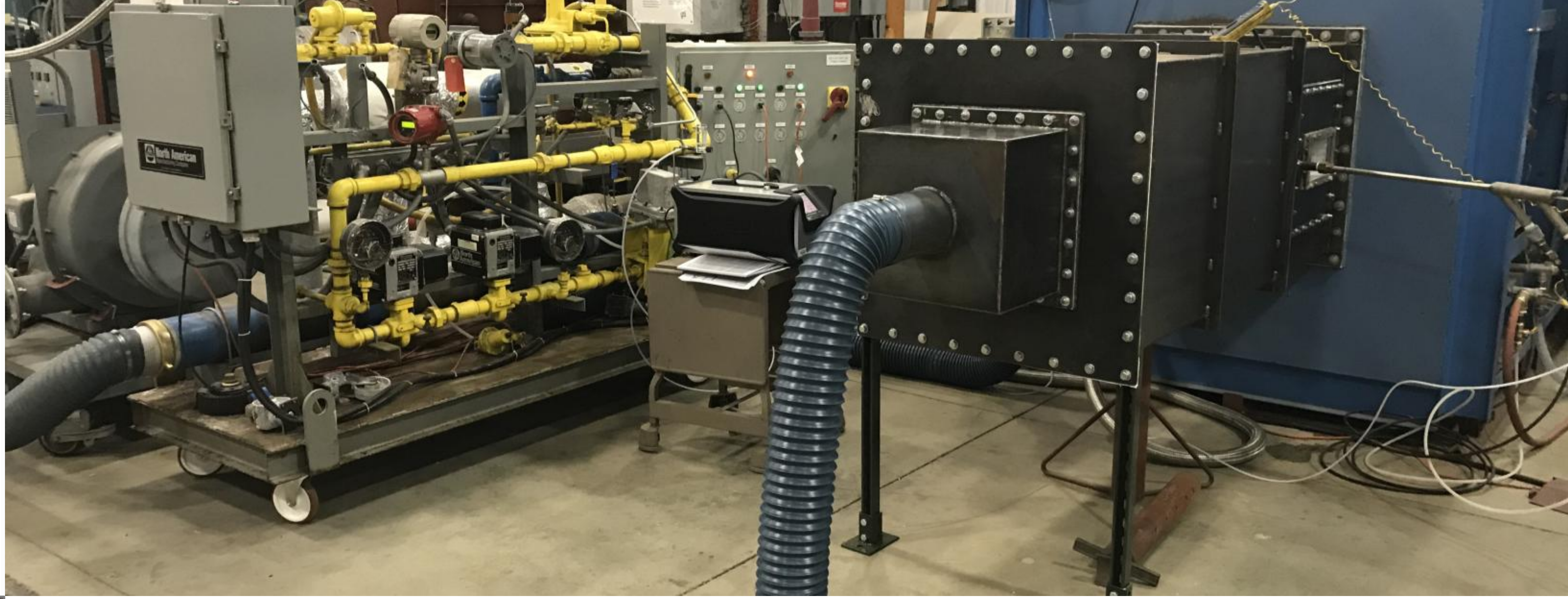

# Decarbonizing Commercial and Industrial Heating with Hydrogen

## Part 1 – Fundamentals, Materials Impacts, and Commercial Cooking/HVAC Test Results


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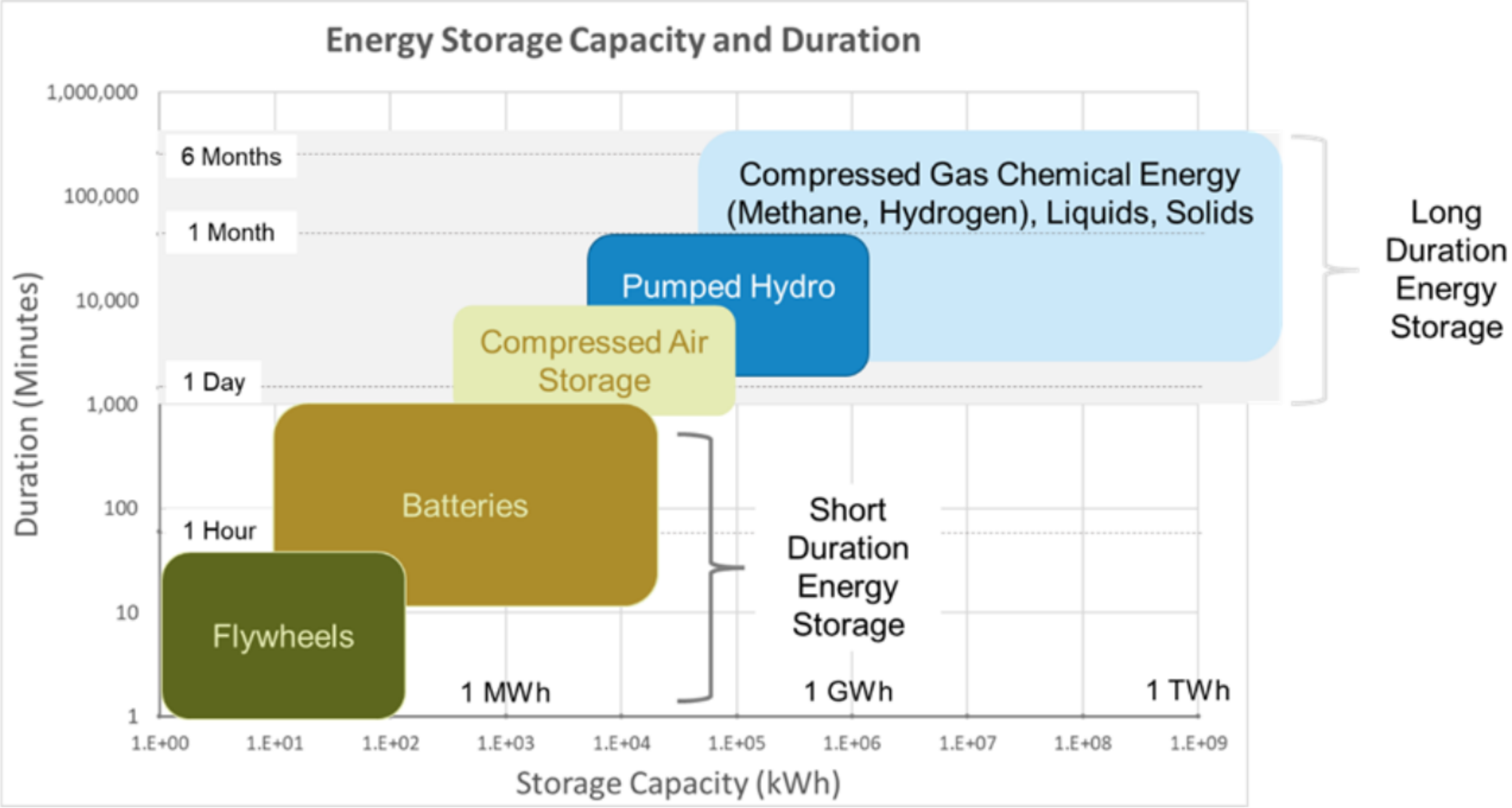
Prof. Vince McDonell, **Univ. of California Irvine**


February 11, 2025

# Decarbonize our Largest Energy Storage Asset

**North American Gas Infrastructure**

- Spans 5.4e6+ km
- Serves 85+ million buildings
- Delivers 600+ GW of peak energy
- Stores 1.3+ PWh over months
- Results in >1,000 MMT $CO_2$/y (heat)
- Can play a constructive and resilient role in **decarbonization**, in transition and in the future




Data Sources: U.S. Census, U.S. DOE-EIA, U.S. HUD, Enerdata, NREL, LLNL; Figure Source: Liss, W. (2022). Long-Duration Utility-Scale Energy Storage, Report Prepared by GTI Energy

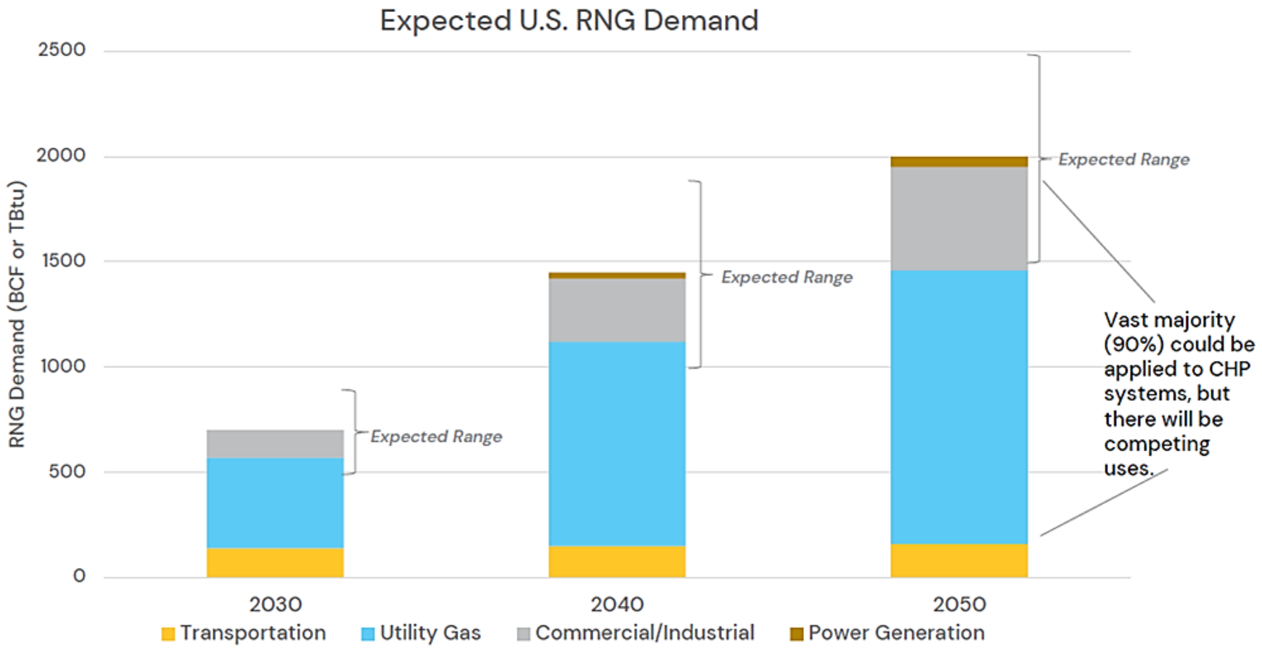
# Decarbonize our Largest Energy Storage Asset

**Hydrocarbons: Drop-in for Natural Gas/Propane with *Net* GHG reductions**

- RNG/Biomethane, Bio-LPG, Biodiesel **available today** in many markets, SNG/E-methane projects underway, investigating *trace contaminant* impacts

**Hydrogen: Not a Drop-in but with *Absolute* GHG Reductions**

- ***Most*** States/Provinces have $H_2$/NG blending demo projects in planning or underway, involving 100s – 10,000s of utility customers




**States/Provinces with 1+ Active $H_2$ Blending/Distribution Projects**

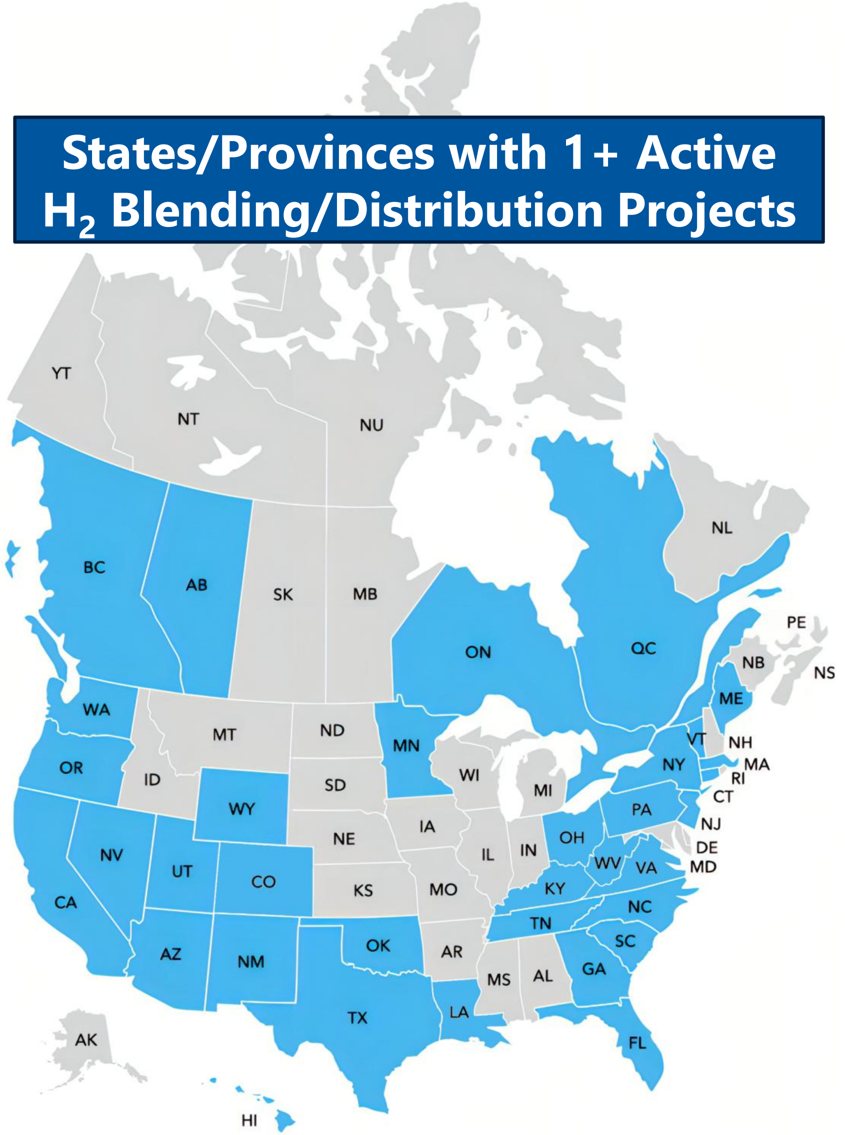
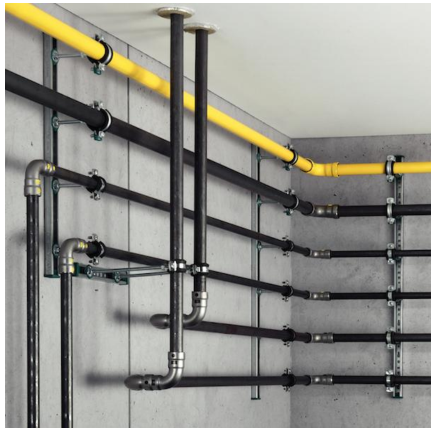



Image source: DOE-IEDO, ICF, AGA

# Hydrogen Economy – The Industry is Moving Fast!

**Gas Train:** Full product line OK for 25% $H_2$ today, 100% $H_2$ available



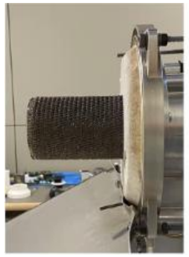
**Customer Distribution:** System options for 0-100% $H_2$ available today

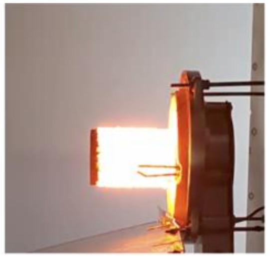
## Heating Industry is Increasingly $H_2$-Ready

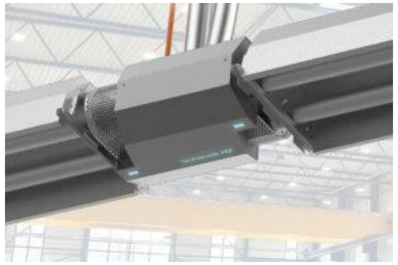
Product / Technology Demonstrations


**Combustion Controls and Sensors:** Full product line OK for 30% $H_2$ today, 100% $H_2$ available in a range of applications

**Burners:** Most vendors have burners certified with G222 (23% $H_2$), many have developed 100% solutions, with industry guidance on designs widely available.







**Equipment:** Some have 'self-certified' to blends, 20%-30% $H_2$ in NA (cert. possible now), nearly all end use categories have 100% $H_2$ developed for sale/demo

Customer Distribution → Gas Train → Combustion Controls → Burners and Equipment

# Project Overview – PIR-22-001

## California-Focused Project

Large effort to quantify the potential of hydrogen to decarbonize **large buildings and industry in California**:

- Develop techno-economic roadmap to decarbonize **~50%** of CA's nat. gas use
- Large effort across diverse team to:
  - Develop CA-specific TEA for $H_2$ use, quantify potential/costs of conversions to $H_2$
  - Test/model $H_2$ tolerance of wide range of large equipment categories (e.g. boilers)
  - Material testing for long-term impacts
  - Air Quality simulation on regional impacts
  - Stakeholder outreach and engagement

**Decarbonizing Large Commercial and Industrial Equipment with Hydrogen (PIR-22-001)**

California Energy Commission · GTI Energy · UC Irvine · EPRI Electric Power Research Institute · AHRI Air-Conditioning, Heating, & Refrigeration Institute · SoCalGas · PG&E Pacific Gas and Electric Company · Southwest Gas · UTD Utilization Technology Development · LCRI Low-Carbon Resources Initiative

Test Equipment Selection

- 2+ units per equip. category
- Finalized after Preliminary TEA

**Commercial Examples:**

- Furnaces/Weatherized HVAC
- Water Heater/Hot Water Boilers
- Cooking / Catering Equipment

**Industrial Examples:**

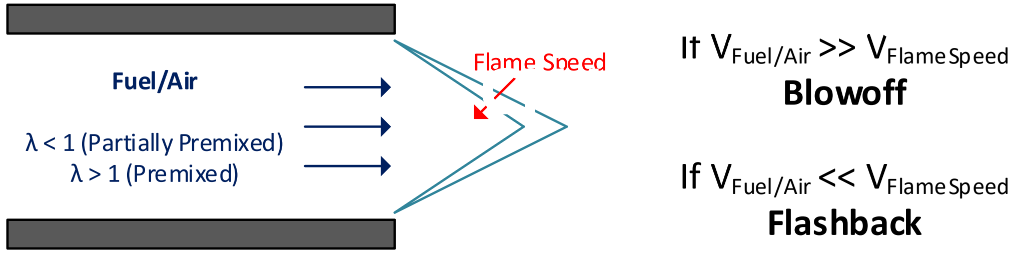
- Steam Boilers / Process Heaters
- Ovens / Dryers / Kilns
- Heat Treating / Furnaces

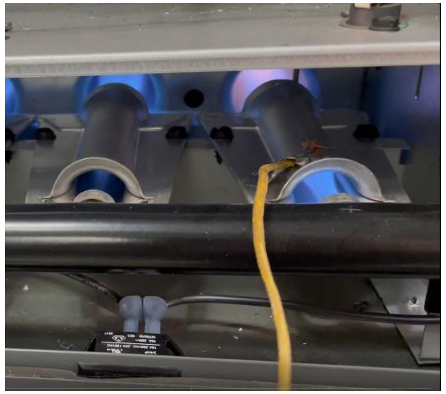
# Project Motivation – PIR-22-001

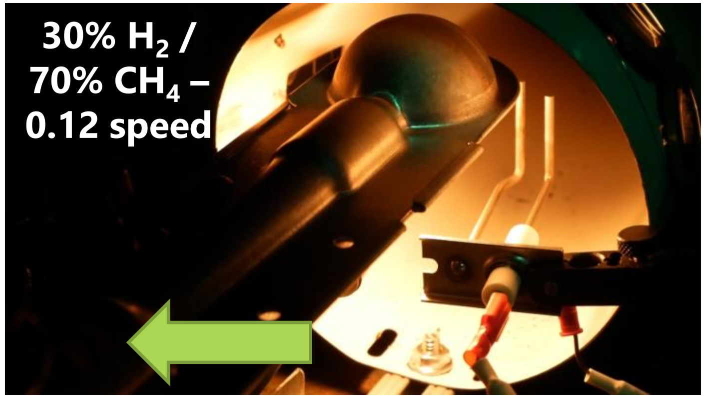
## What do we typically look for with $H_2$?

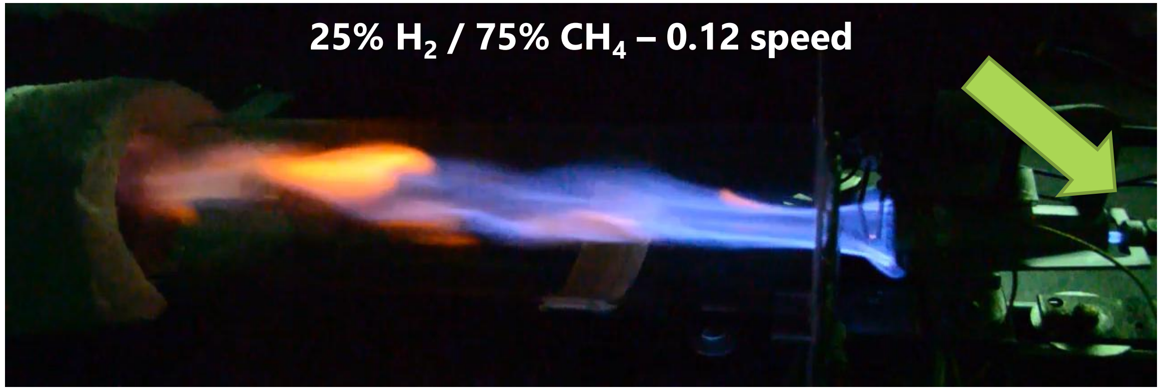
- Short-duration testing looks at…
  - Flame stability/safe ignition/flashback
  - Surface temperatures/Radiant Output
  - Capacity/Efficiency/Modulation
  - Emissions ($NO_x$, CO, $CH_4$, or $H_2$)
  - Impact of variable blending/balance fuel
  - Static leakage enhancement
- But what about…
  - Higher blends/pure hydrogen? Long-term impacts? Testing to failure?
  - Broader population of equipment (type, age, installation)? Emerging technologies and retrofit packages? Impact on industrial processes?

**Simplified Flame**






* For review of H2/NG impacts on combustion equip., see GTI paper: https://www.mdpi.com/1996-1073/15/5/1706

# First Goal – Establish the Decarb. Potential

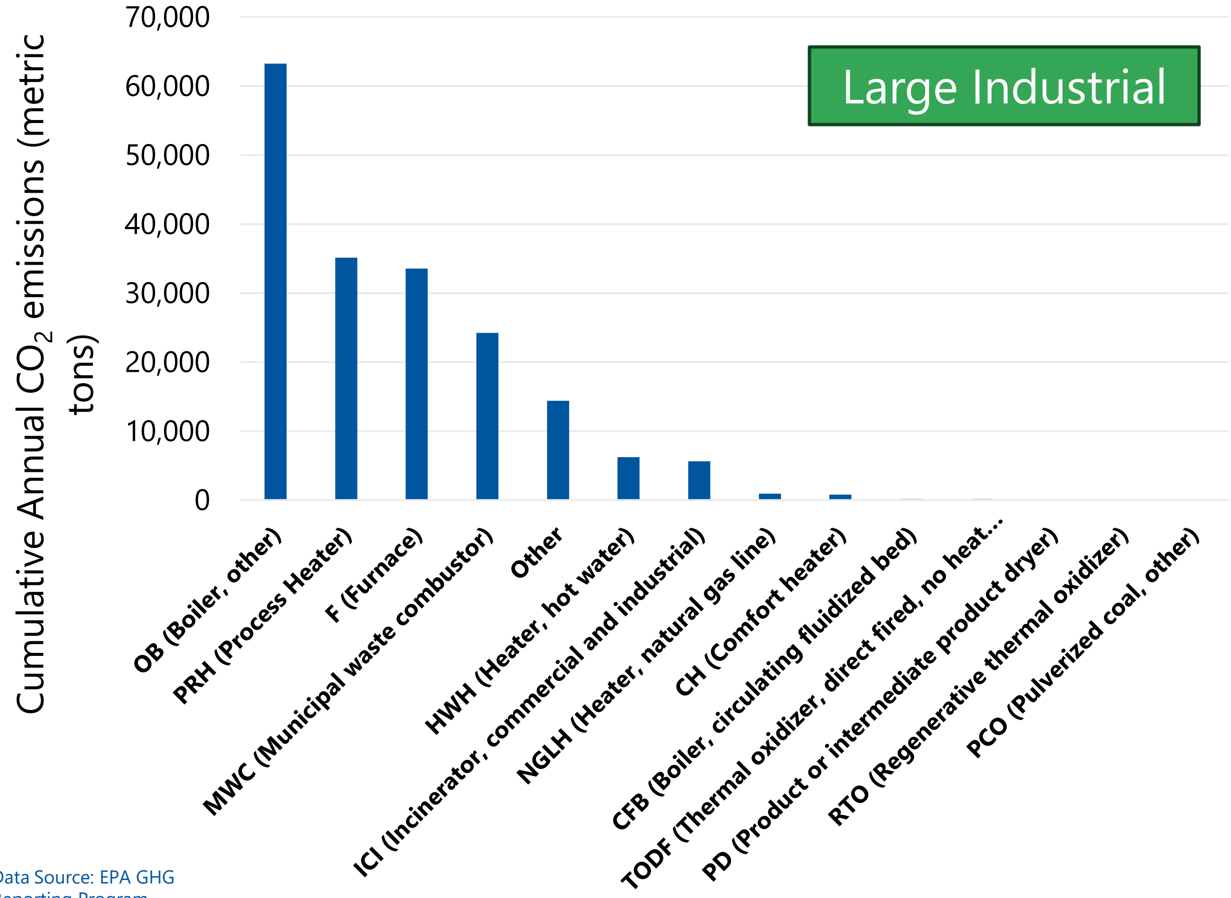
Goal of the task-level effort was to recommend equipment categories/applications for further investigation **based on GHG reduction potential with $H_2$-based fuels**

- Establish a CA-specific *Combustion Equipment Database* for TEA and broader project
  - Draft based on EPA, AQMD/APCD sources, continuing to seek data from CA IOUs and industry
- *Preliminary Techno-Economic Assessment* provides GHG potential of adapting $H_2$-based fuels in CA C&I sectors
  - EPRI model built and calibrated to DOE/CA databases (e.g. CBECS)
  - Using prior database and range of decarbonization scenarios, quantify energy/cost/emissions for:
    - **Natural Gas:** Reference Case, Maximum Achievable Energy Efficiency (MAEE)
    - **Low Carbon Fuels:** Blended Case (NG / RNG / $H_2$), Blended Case w/ MAEE, 100% $H_2$ w/ MAEE
    - **Alternative:** Partial Electrification (w/ LCFs), Widespread Electrification

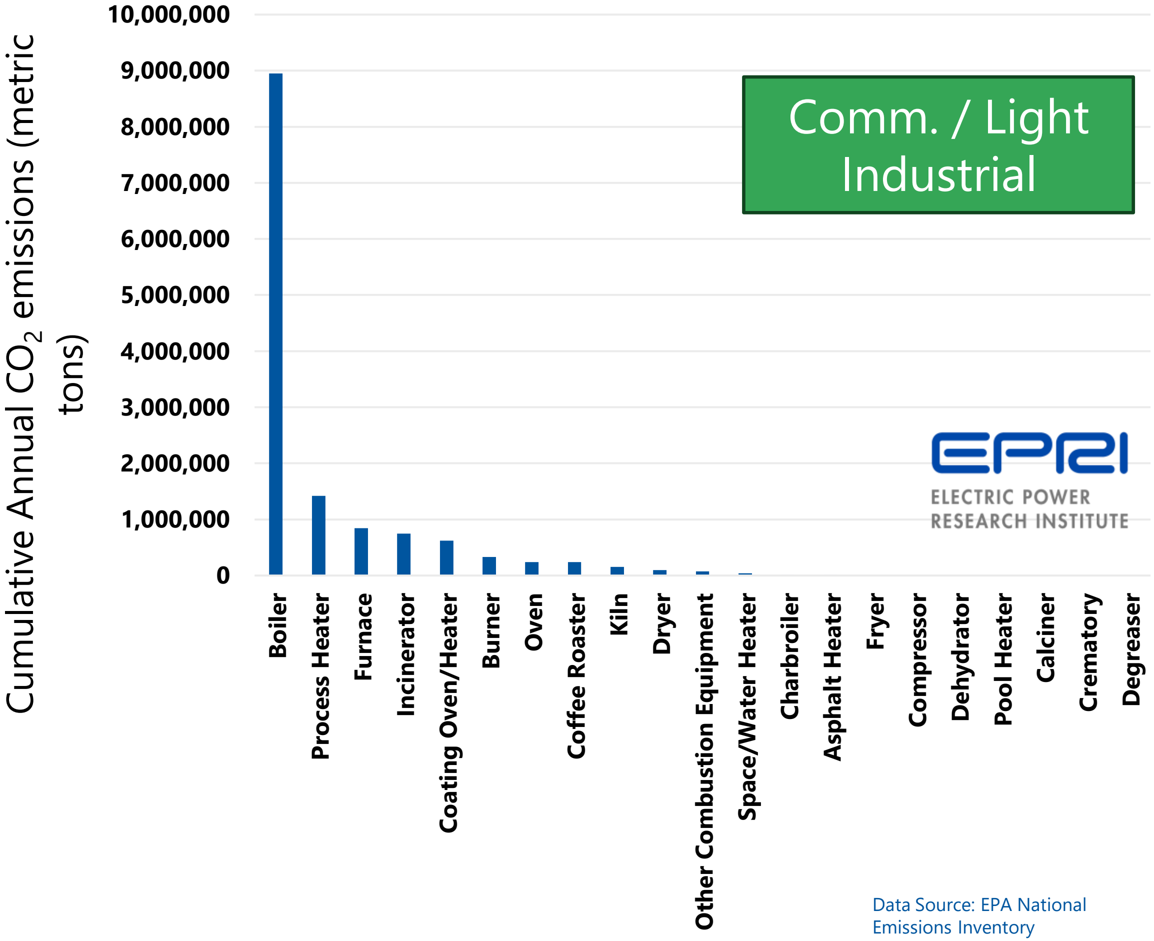
Results discussed in 2nd session

# Preliminary Results – Database (Comm. / Industrial)

**Draft/Preliminary Results: Subject to Change**




Data Source: EPA GHG Reporting Program




ELECTRIC POWER RESEARCH INSTITUTE

Data Source: EPA National Emissions Inventory

Boilers, Process Heaters and Furnaces have highest cumulative $CO_2$ emissions and highest equipment counts

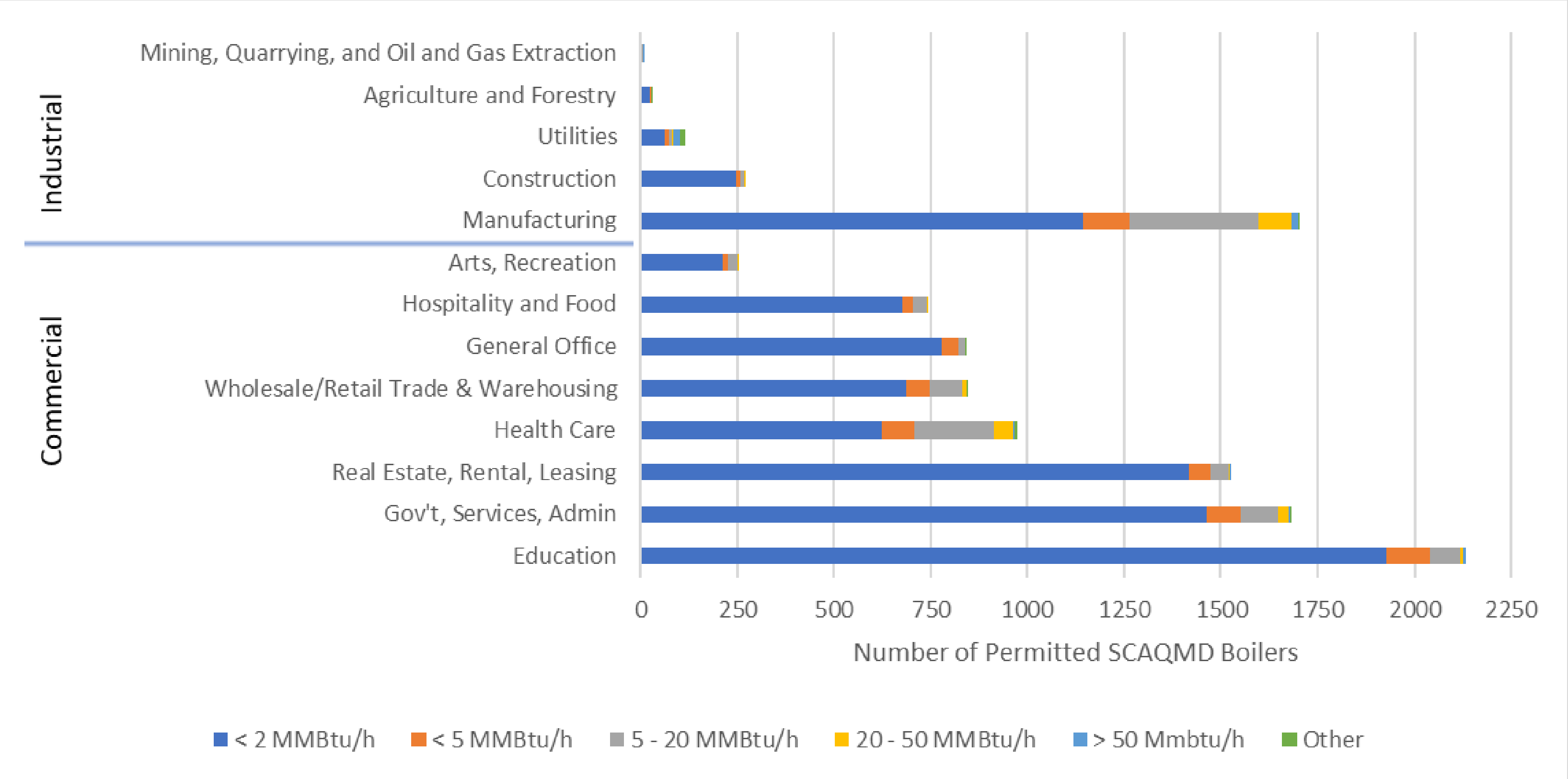
# Preliminary Results – Database (Continuation)

**Draft/Preliminary Results: Subject to Change**

Project team sought further granularity/detail through local agency, utility, and industry group data sources, below is AQMD example to emphasize the importance of **boilers overall**

There are **even more** boilers beyond EPA permitting, typ. OEM-certified, more than 10X this estimate. Within the SCAQMD:

- 97% (10,800) are ≤20 MMBtu/h
- 99% are ≤50 MMBtu/h
- The combined energy demand of all these boilers ≤50 MMBtu/h is ~15 GW - Appx. 1/3 of the 2021 CAISO peak.




Data Source: SCAQMD

# Second Goal – Filling the Gaps in the Data

Recommend equipment categories/applications for further investigation **based $H_2$ utilization potential and data/knowledge gaps**

- ***Technical Survey of Performance, Safety, and Emissions Impacts***
  - Review the efficiency, operability, emissions, and safety impacts of combustion equipment operating with $H_2$-blended natural gas and, if suitable, 100% hydrogen
  - Survey equipment/operational modifications to **tolerate higher blends of hydrogen**
  - Identify research and technology gaps, concerning hydrogen utilization in key equipment categories/applications, **provide basis for test planning**
- Scoping of survey and recommendations for testing program:
  - Large HVAC* equipment (commercial warm-air furnaces, rooftop units, unit heaters), Commercial cooking equipment – **Covered in Session 1**
  - Industrial furnaces, Process ovens and dryers, other Industrial stationary combustion equipment, Boilers (hot water and steam), Water Heating - **Covered in Session 2**

*Per the CEC, "Large Commercial Building" is defined as a non-residential building with 100,000 $ft^2$ of floor space or greater.

# Testing Program – Filling the Gaps in the Data

**Testing and Analysis Program:**

- Test rigs for **six categories** of large commercial/industrial heating equipment underway now
- Examples of natural gas equipment tested with increasing hydrogen **two ways (on / off rate)** over 2024
  - Data collected on perf., emissions ($NO_x$, CO, $\mathbf{CH_4}$, $\mathbf{H_2}$), noise, etc.
  - Evaluate retrofit options for higher $H_2$
- Calibrate **CFD combustion model** for extrapolation to equipment/designs
- Investigate **impact on materials** (e.g. refractory) in parallel

| Equipment Type | Sub-type(s) | Coverage Range | Test Unit Range |
|---|---|---|---|
| **Boilers** | Steam<br>Hydronic/Hot Water | Up to 50 MMBtu/h input | 300 to 3,000 kBtu/h input |
| **Direct-fired Process Heating** | Ovens, kilns, and dryers | Up to 100 MMBtu/h input | 500 to 2000 kBtu/h input |
| **Industrial Furnaces** | Recuperative / Non-recuperative Burners | Up to 100 MMBtu/h input | 500 to 2000 kBtu/h input (200 to 500 kBtu/h Radiant tube) |
| **Commercial HVAC** | Warm-air Furnace, Duct Furnaces, & Unit Heaters | 200 to 1,000 kBtu/h | |
| **Commercial Cooking** | A range equip.: fryers, broilers, griddles, ovens, charbroilers, and ranges | 100 to 500 kBtu/h | |

**Increasing GHG Impact in CA**

# Decarbonizing Commercial and Industrial Heating with $H_2$

## Session #1 (1:30p-2:30p)

**"Hydrogen 101" (UCI)**

- Review the fundamentals of hydrogen combustion relative to conventional fuels
- Understand the potential impacts on a variety of burner and combustion system designs

**Research Project Plan & Results (UCI)**

- Discuss the potential short/long-term impacts on materials within heating equipment
- Review the experimental test plan and preliminary results for Commercial Cooking and Commercial HVAC equipment

## Session #2 (3:00p-4:00p)

**Research Project Plan & Results – Cont. (GTI)**

- Review the experimental test plan and preliminary results for Industrial Combustion Equipment, Boilers, and Water Heaters

**Hydrogen – OEM Perspective (A.O. Smith)**

- Manufacturer perspective on $H_2$ applied to heating equipment and testing results

**Pulling it All Together – $H_2$ Big Picture (GTI)**

- Putting research data into broader context, including techno-economics, codes & standards, trends in test data, and $H_2$ safety

# AHR Session
# Decarbonizing Commercial and Industrial Heating with Hydrogen

UCI Combustion Laboratory

UCIrvine | University of California

Vincent McDonell

# UCI Combustion Laboratory

- History
  - Founded in 1970 (Scott Samuelsen)
    - ✓ Reconcile conflict between Energy and the Environment
  - Initial focus on Aeroengines/Alternative Fuels
  - Stationary Power/Alternative fuels
- High Hydrogen Content Fuels
- Extensive Experimental Research Facilities


Word Cloud of Recent Paper Titles

Air compressors (4 lb/s 1000 F)

Fuel mixing station ($H_2$, CO, $CH_4$, etc): 250kW

Test cells (10, 20,000 sq ft)

DG test area

Fuel compressors (to 500 psi)

Liquid fuel storage/pumps (biodiesel, SAF)

DG test area (1 MW generation)



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# “$H_2$ 101” - Fundamentals

- **Hydrogen differs from the natural gas we are used to working with**

| | **Methane** | **30% Hydrogen 70% Methane** | **Hydrogen** |
|---|---|---|---|
| **Molecular Weight (g/mol)** | 16 | 11.8 | 2 |
| **Density (lbm/ft$^3$)** | 0.042 | 0.031 | 0.0053 |
| **Higher Heating Value (Btu/ft$^3$)** | 1014 | 806 | 325 |
| **Wobbe Index (Btu/ft$^3$)** | 1361 | 1261 | 1232 |
| **Stoichiometric Air-fuel Ratio ($AF_{st}$) (v/v)** | 9.5 | 7.4 | 2.4 |
| **Lower Flammability Limit (LFL) (% vol in air)** | 5% | 4.7%[a] | 4% |
| **Upper Flammability Limit (UFL) (% vol in air)** | 14% | 19%[a] | 75% |
| **Quenching Distance ($\lambda$=1) (in)** | 0.079[b] | 0.069[b] | 0.025[b] |
| **Minimum Ignition Energy in Air ($10^{-5}$ J)** | 20[c] | 10[c] | 2[c] |
| **Adiabatic Flame Temperature ($\lambda$=1) (°F)** | 3542 | 3575 | 3807 |
| **Laminar Flame Speed ($\lambda$=1) (ft/min)** | 75[d] | 94[d] | 463[d] |
| **Min. Detonation Cell Size ($\lambda$=1, 68°F) (in)** | 12[e] | 7[e] | 0.4[e] |

a – Based on Le Chatelier’s rule [2]
b – Fukuda et al [3]
c – Hankinson et al [4]
d – Calculated using GRI-Mech 3.0 [5] and Cantera [6]
e – Matignon et al [7]



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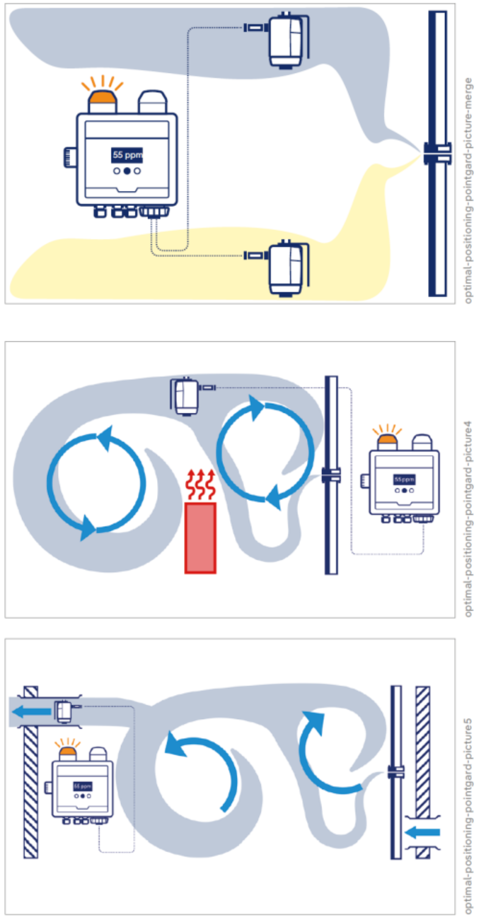
# “$H_2$ 101” - Fundamentals

- **Implications/Questions regarding density/MW**
  - Dispersion, segregation
  - Leaks/accumulation
    - ✓ hydrogen can gather near ceilings of enclosed spaces, etc
    - ✓ Combined with range of flammability, considerations for ventilation/sensor locations
  - Will H2/NG stratify in pipelines?
    - ✓ Molecular diffusion suggests no
      - – Gases are not like liquids (oil / vinegar)
    - ✓ Empirical evidence
      - – Analyzer span gases
      - – Several recent studies
  - Will H2 leak preferentially from pipes, etc?
  - Will H2 interact with metals?

Different scenarios which are typi-cal for gas leaks within a building




Air tight room; light gas „blue“, dense gas “yellow”.

Thermal source devel-oping convection cur-rents.

Room with ventilation system.

Source: Dräger (2008), Gas Dispersion, STL-1168



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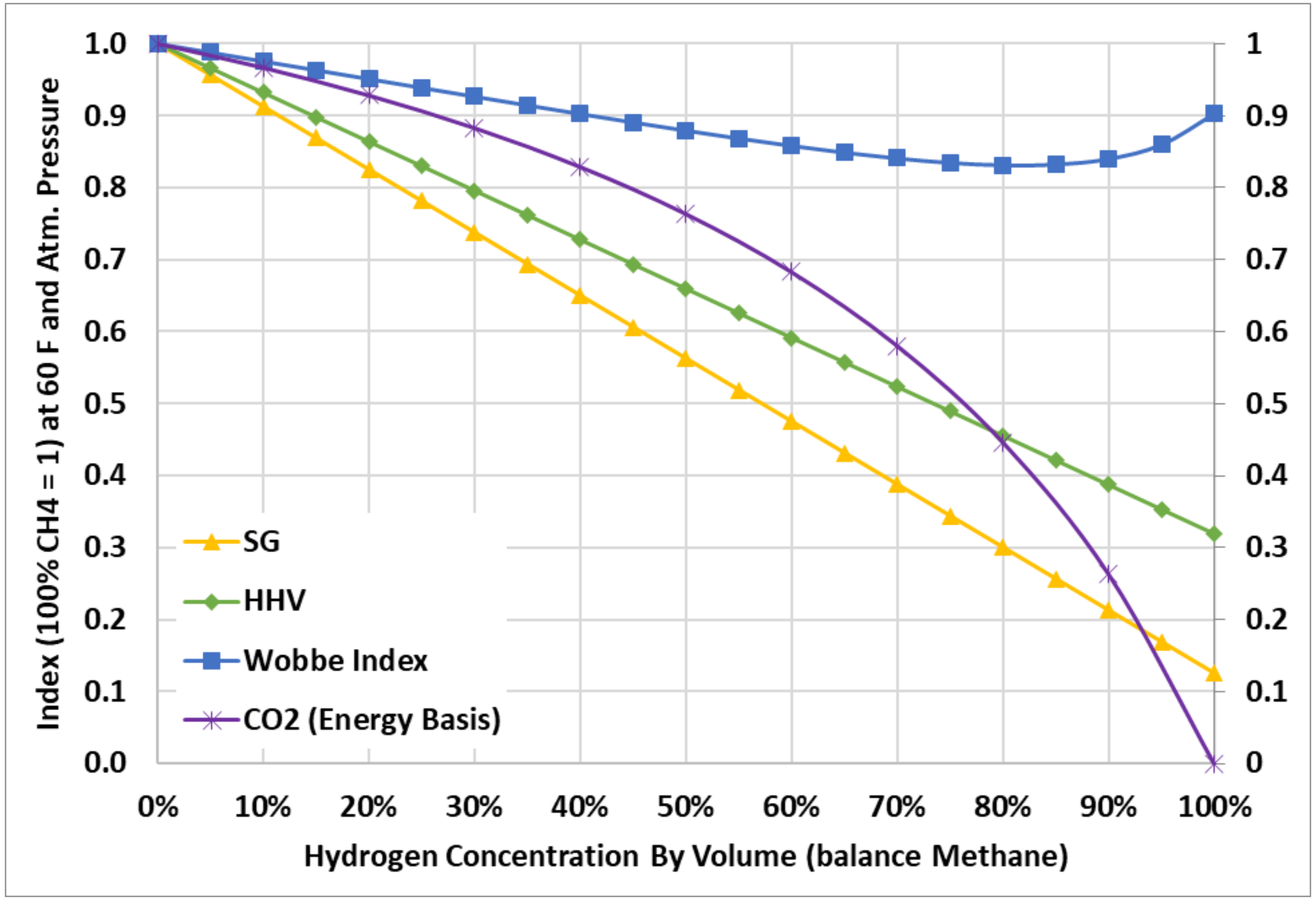
# "$H_2$ 101" - Fundamentals

- **Interchangeability**
  - **Hydrogen is relatively interchangeable with natural gas (Wobbe Index)**
  - **Must flow <u>3x volume to match gaseous heat input</u>**




Source: GTI Energy

$$Wobbe = \frac{HHV}{\sqrt{S.G.}}$$

- How many BTUs can I get through a given orifice diameter with a given feed pressure?



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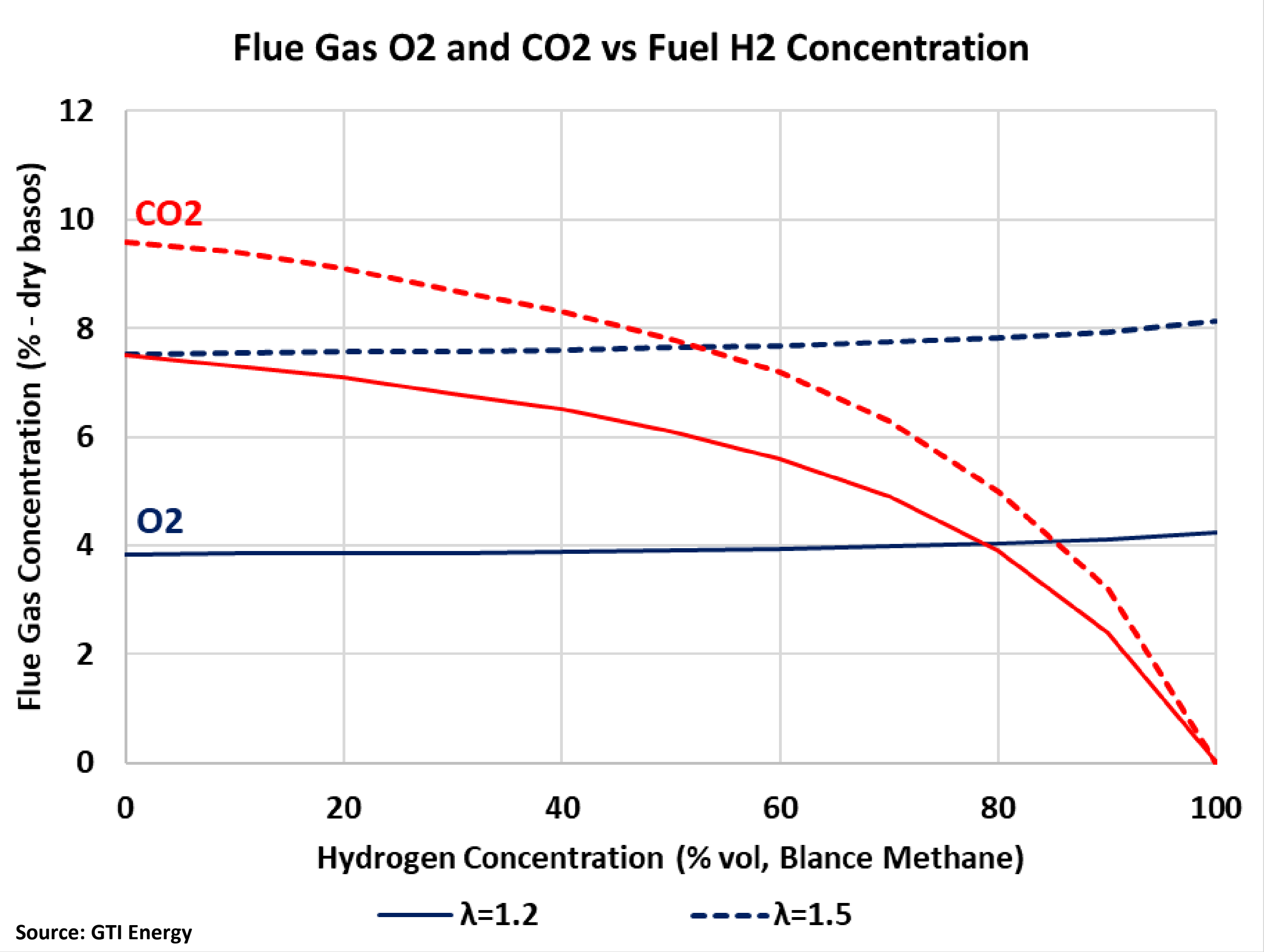
# “$H_2$ 101” - Fundamentals

- **Air to Fuel Requirements**
  - **Hydrogen requires about 24% less air to fully react than does natural gas**




$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

$$H_2 + 0.5(O_2 + 3.76N_2) \rightarrow 2H_2O + 1.88N_2$$

<u>0.5</u> parts $O_2$ vs <u>2</u> parts $O_2$

But need ~3x more volume to match heat input
1014 BTU/scf / 325 BTU/scf = 3.12

$$\frac{\dot{V}_{air,H_2,st}}{\dot{V}_{air,CH_4,st}} = \frac{HHV_{CH_4}}{HHV_{H_2}} * \frac{0.5}{2} = 3.12 * 0.25 \approx 0.76 < 1$$



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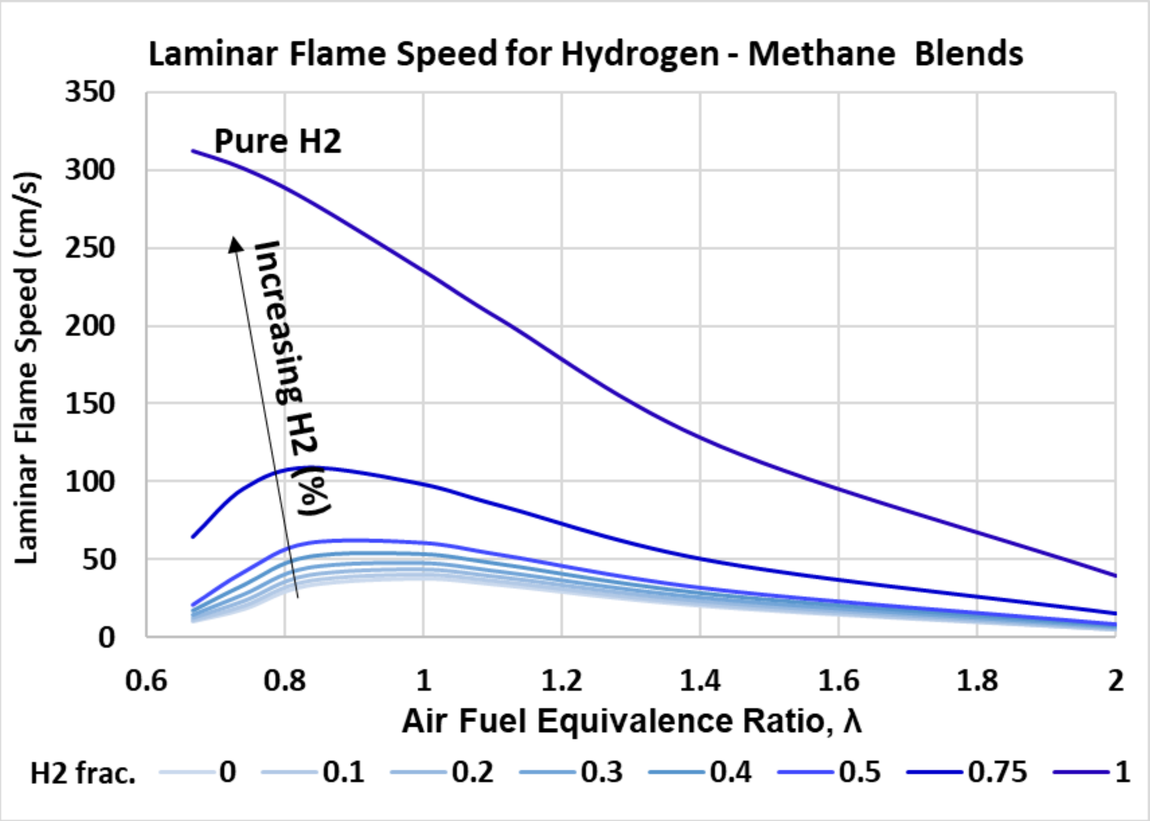
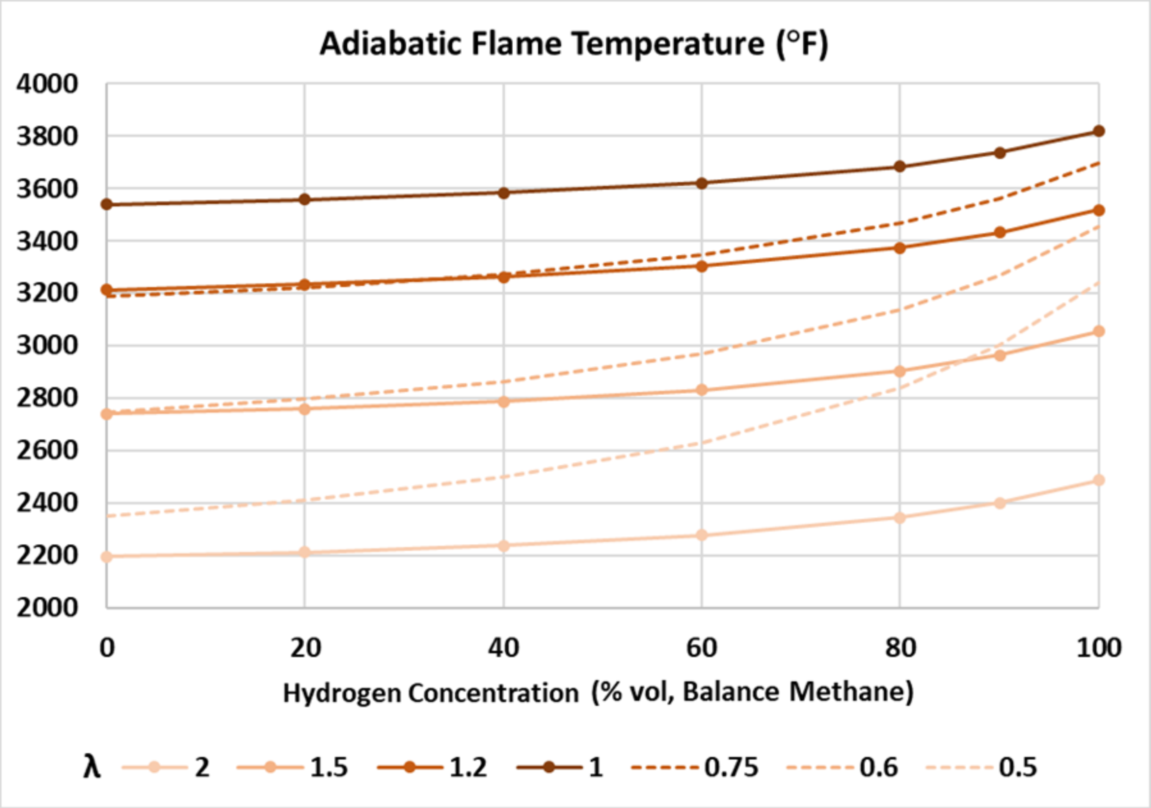
# "$H_2$ 101" - Fundamentals

- **Flame Speed and Flame Temperature**
  - **Hydrogen burns faster and hotter than natural gas (but…..)**




Source: GTI Energy




Source: GTI Energy



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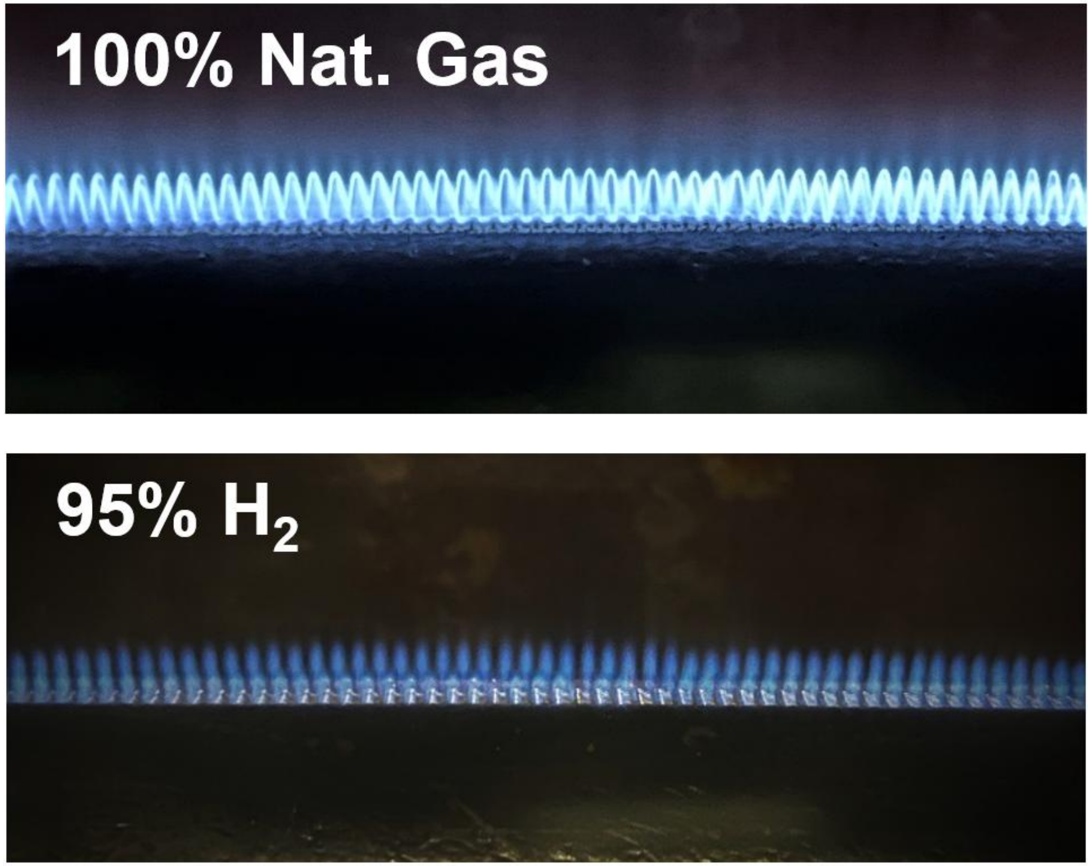
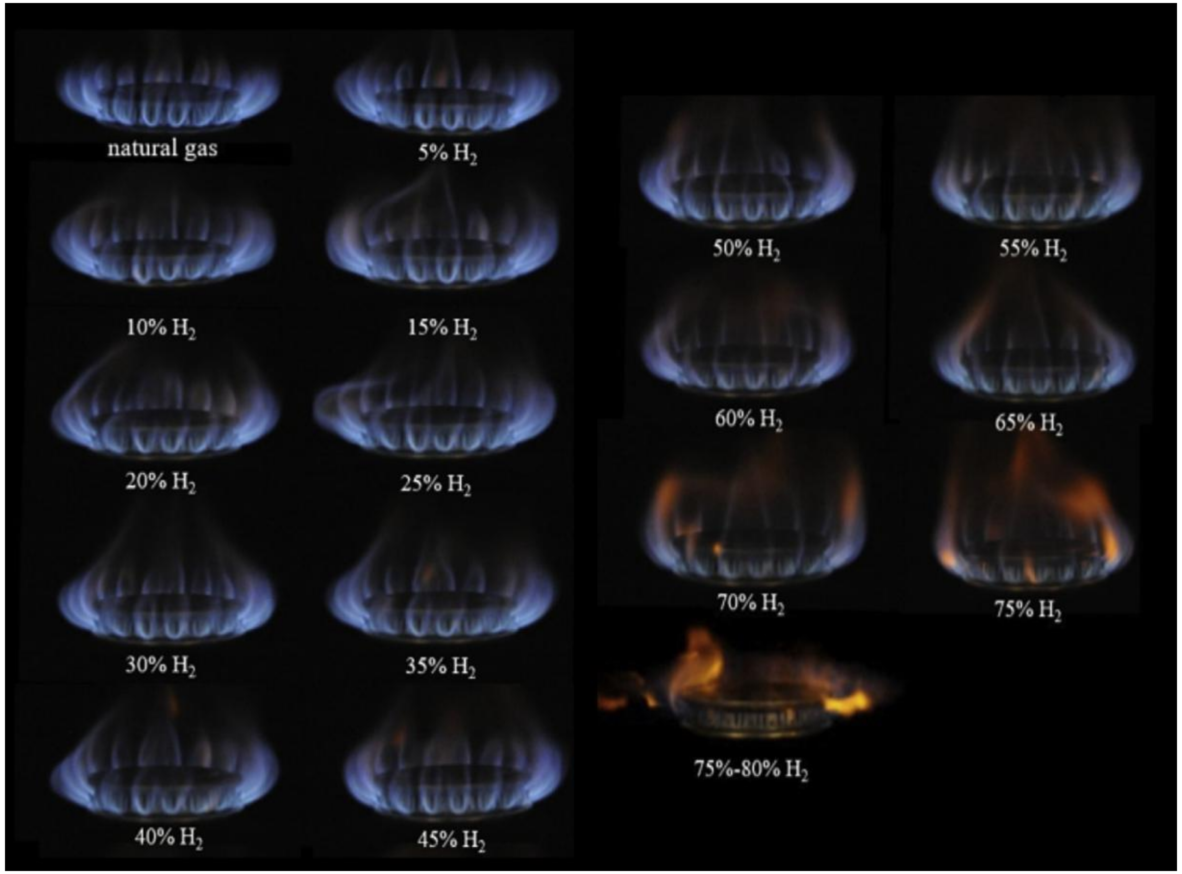
# "$H_2$ 101" - Fundamentals

- **Luminosity differs**




Source: GTI Energy




Source: Zhao, McDonell, Samuelsen (2019). Int'l J Hydrogen Energy, Vol. 44(23), 12239

Hydrogen: colorless, odorless....
What about heat transfer?



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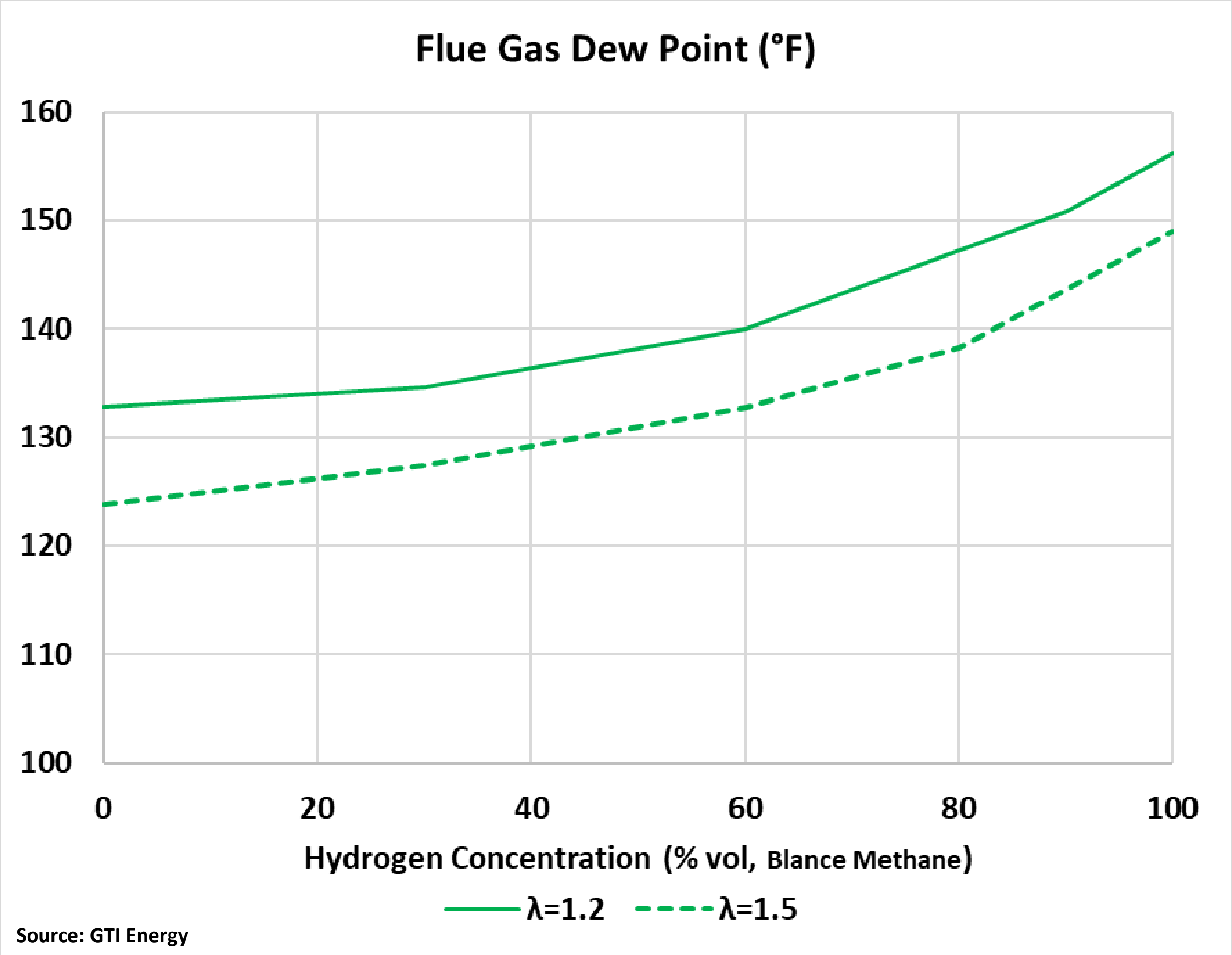
# "$H_2$ 101" - Fundamentals

- **Hydrogen generates higher concentration of water in the exhaust stream than does natural gas**




- Consideration for condensing units
- Materials impact/corrosion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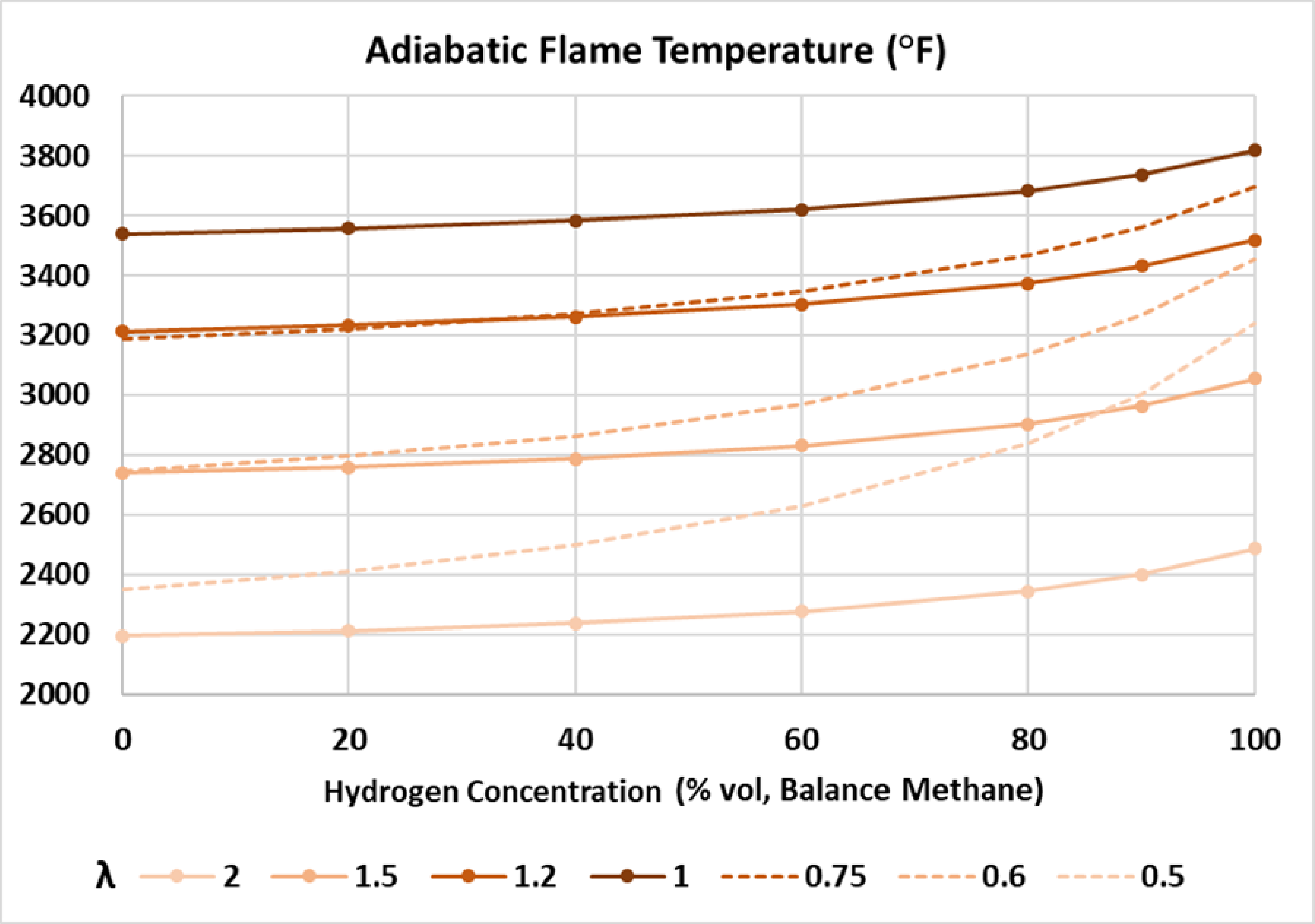
# "$H_2$ 101" - Fundamentals

- **What about NOx emissions?**
  - **Yes—Hydrogen has a higher flame temperature for a given fuel air ratio……but….**




Source: GTI Energy



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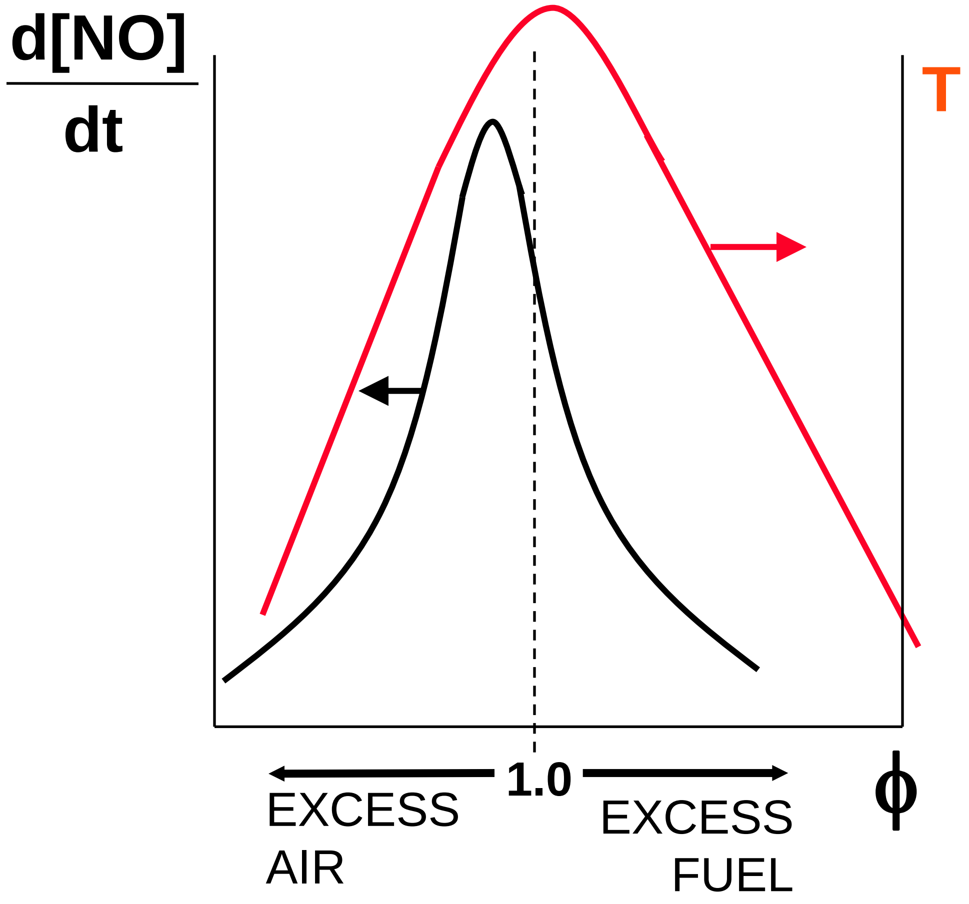
# "$H_2$ 101" - Fundamentals

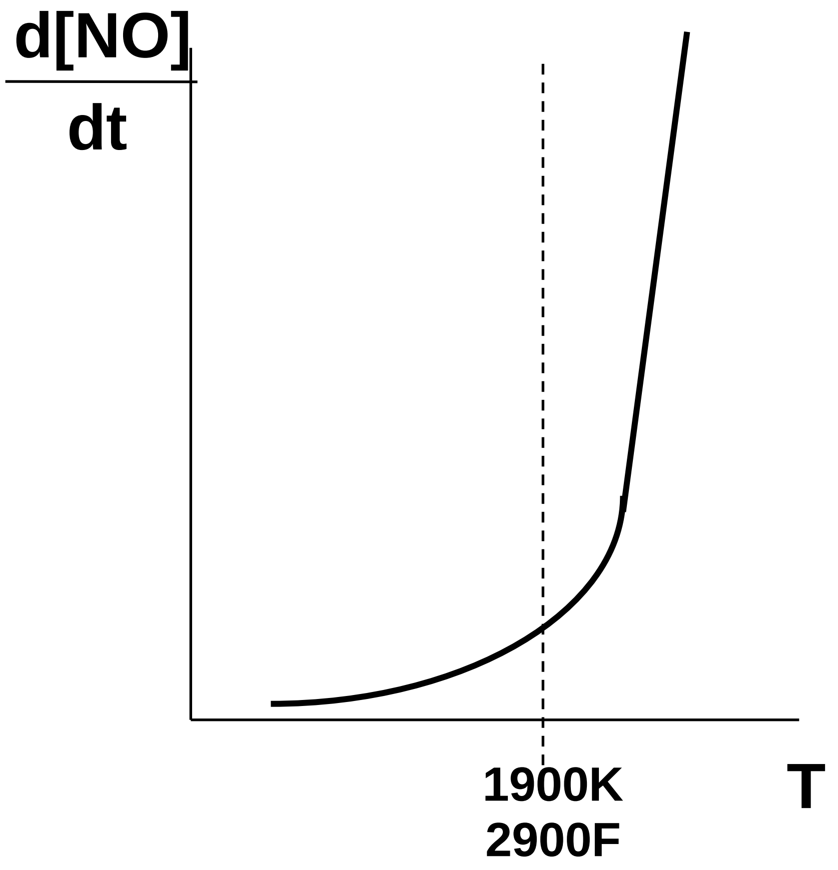
- NOx formation background

$$N_2 + O \longrightarrow NO + N$$

$$N + O_2 \longrightarrow NO + O$$

**High Combustion Temperatures**
**→Enough Energy to Break Triple bonded $N_2$ molecule**




Source: UC Irvine Gas Turbine Short Course



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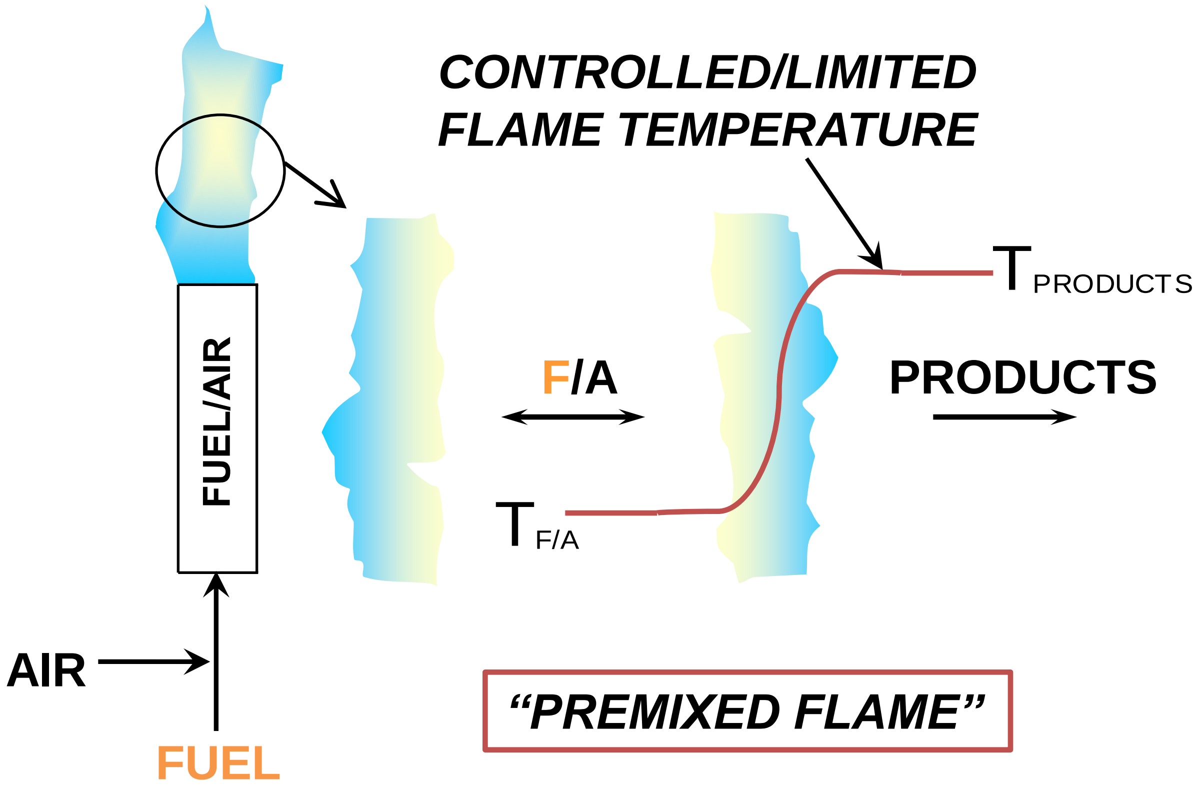
# “$H_2$ 101” - Fundamentals

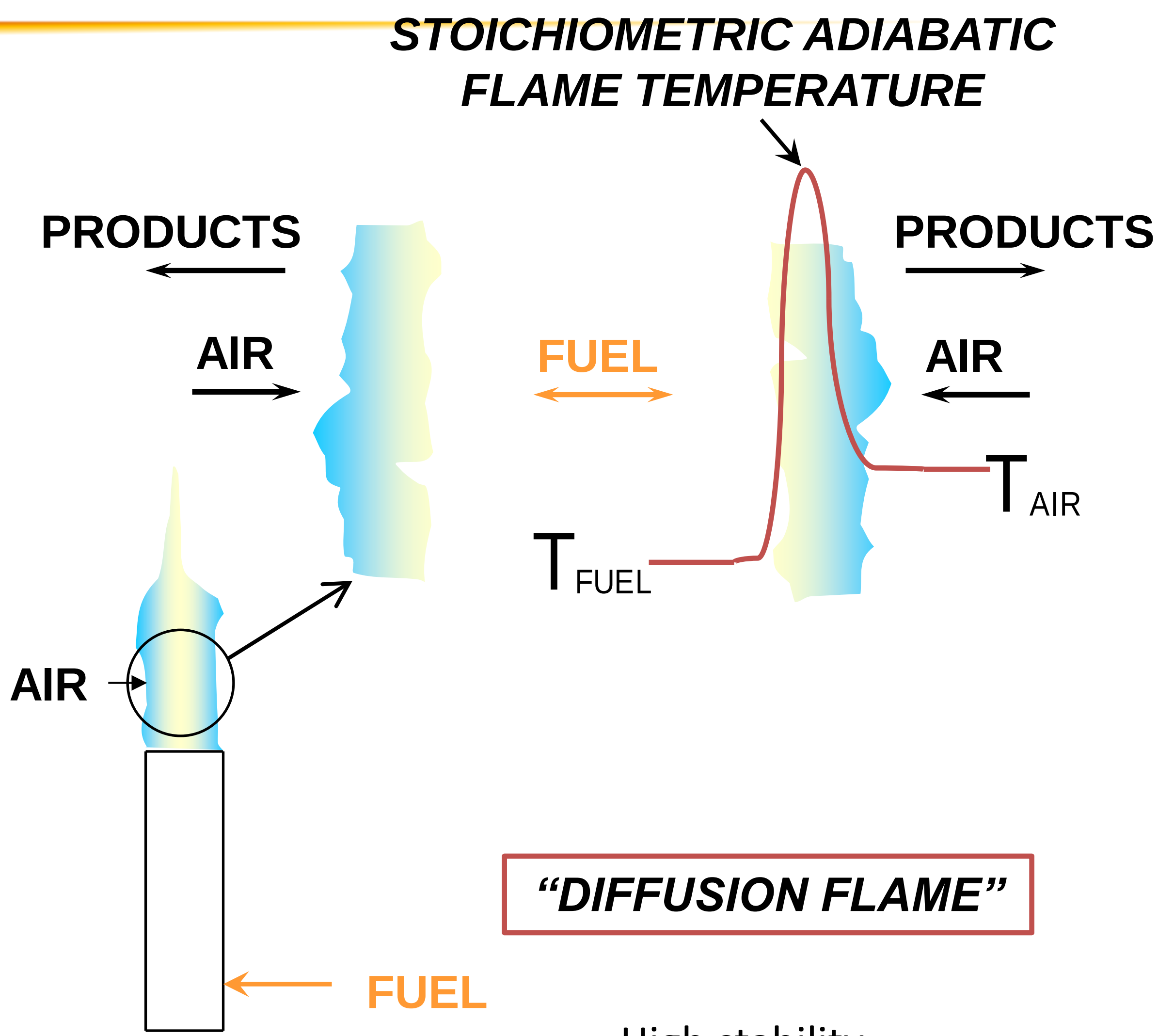
- **Classical Flames**




PREMIXED

Low Emissions
Can be unstable (blow out)

Typical of Low NOx burners




High stability
High NOx emissions



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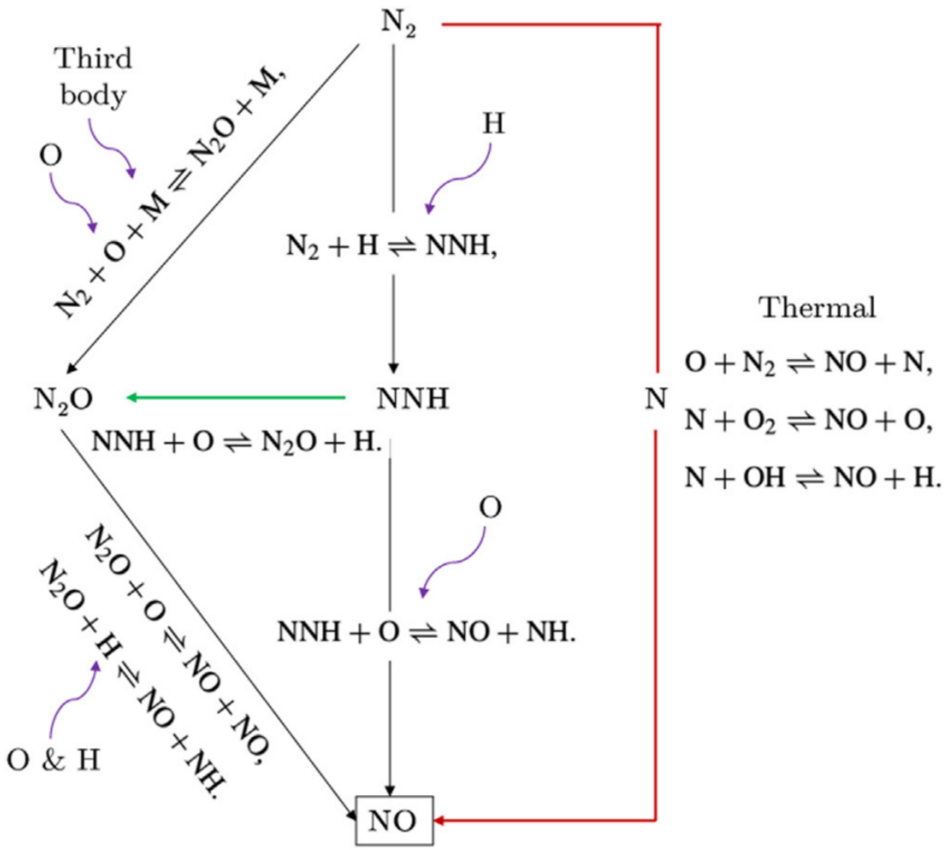
# NOx emissions…a bit more

- **Thermal**
  - **Still the key "intuitive" focus**
  - **Important for all combustion processes**
- **Prompt**
  - **$N_2$ + CH ⇒ HCN + N**
    **(has 25% of the activation energy as thermal)**
  - **Important for $\lambda$ >1.25**
- **$N_2O$**
  - **Important for high pressure lean strategies**
  - **$N_2$ + O + M → $N_2O$ + M     $N_2O$ + O → 2NO**
- **NNH**
  - **Important for Lean $H_2$**
- **Fuel (non issue for NG/H2)**
  - **Important for Coal Gas (Stationary)**
  - **RQL a strategy to mitigate**




**Source: Carpurso, et al. (2023). Combustion and Flame**

NG: Thermal and Prompt
H2: Thermal and NNH



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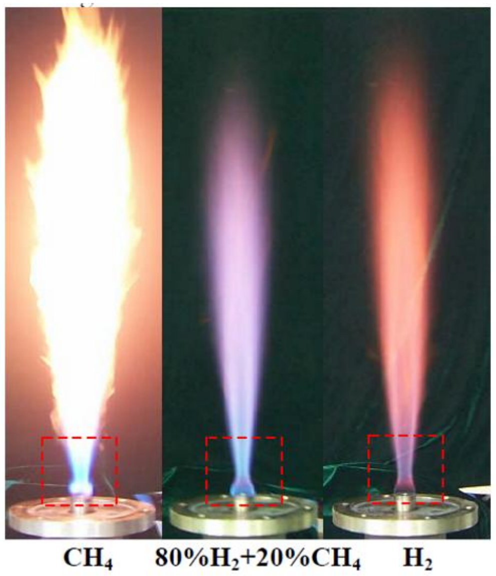
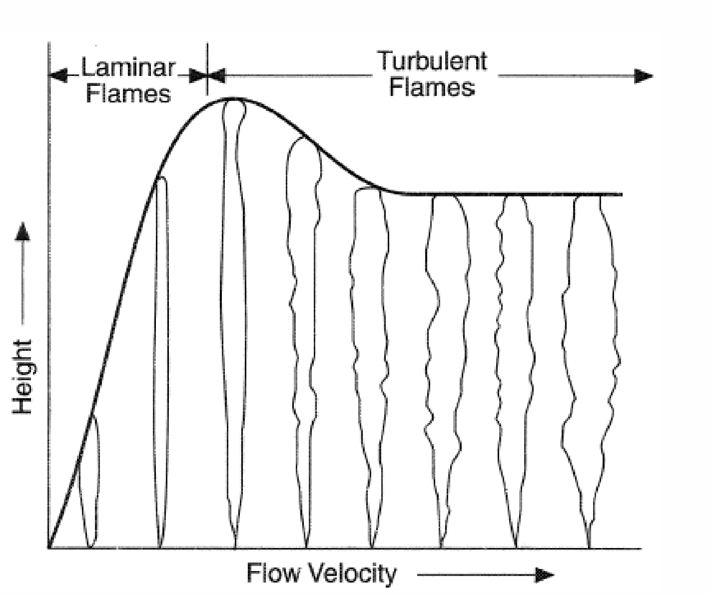
# “$H_2$ 101” - Fundamentals

- **Burner Types vary widely depending on applications**

<u>Diffusion</u>

Inject Pure Fuel
Entrained air mixes and this reacts
Maximum possible flame temps
Turbulence/velocity defines length

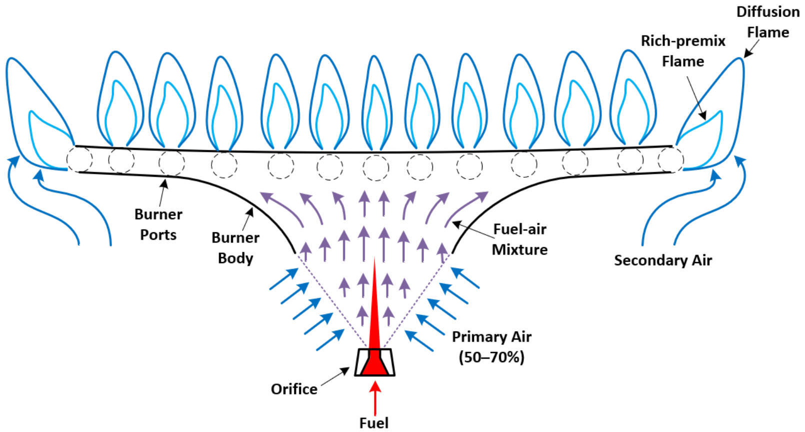



Source: Turns

<u>Partially Premixed</u>

Generally, inject fuel rich (too rich to burn*)
followed by entrained air to burn out remaining fuel




Source: GTI Energy

*wide flammability of hydrogen is a challenge



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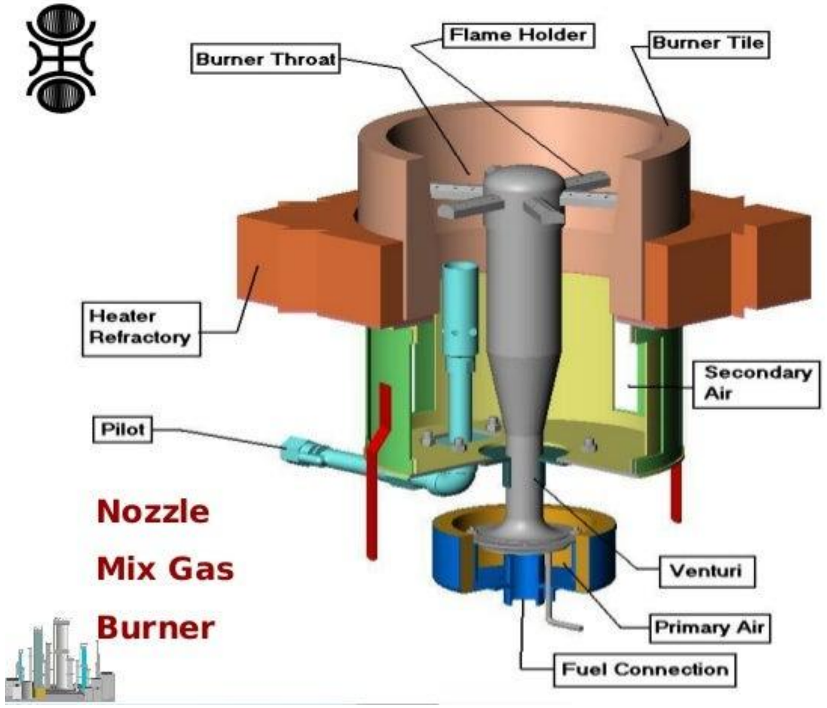
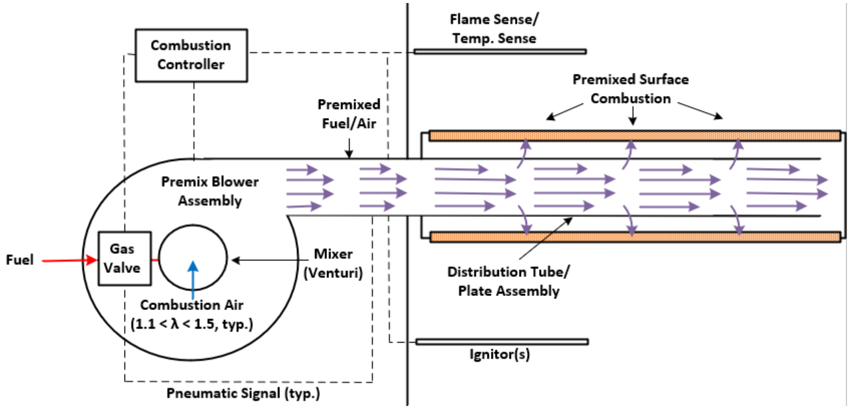
# “$H_2$ 101” - Fundamentals

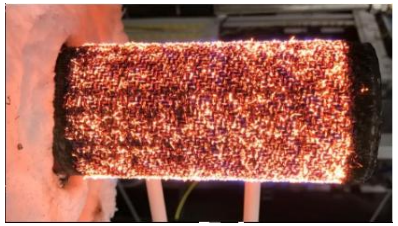
- **Burner Types vary widely depending on applications**

<u>Nozzle Mixed (rapid mix or “LDI)</u>
Operate overall fuel lean
“rapid mixing” near the point of fuel/air injection
Balance safety and emissions




<u>Premixed</u>
Fuel/Air mixed in flammable ratio
“simple” flame temperature control
best NOx performance



Source: GTI Energy



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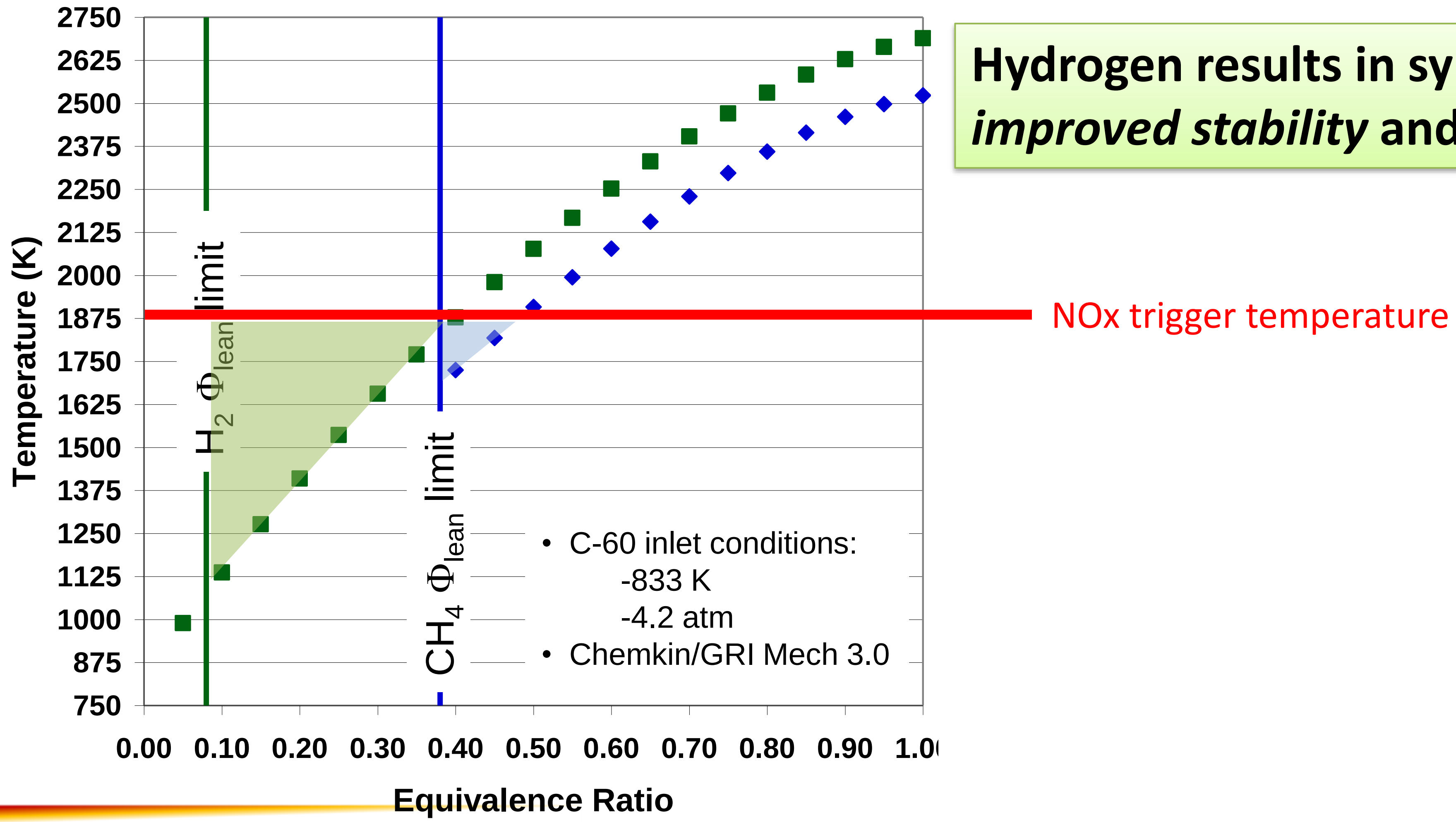
# “$H_2$ 101” - Fundamentals

- **Benefit of wider flammability limits of hydrogen for premixed systems**
  - **Improved turndown**




**Hydrogen results in synergy between *improved stability* and *lower emissions***



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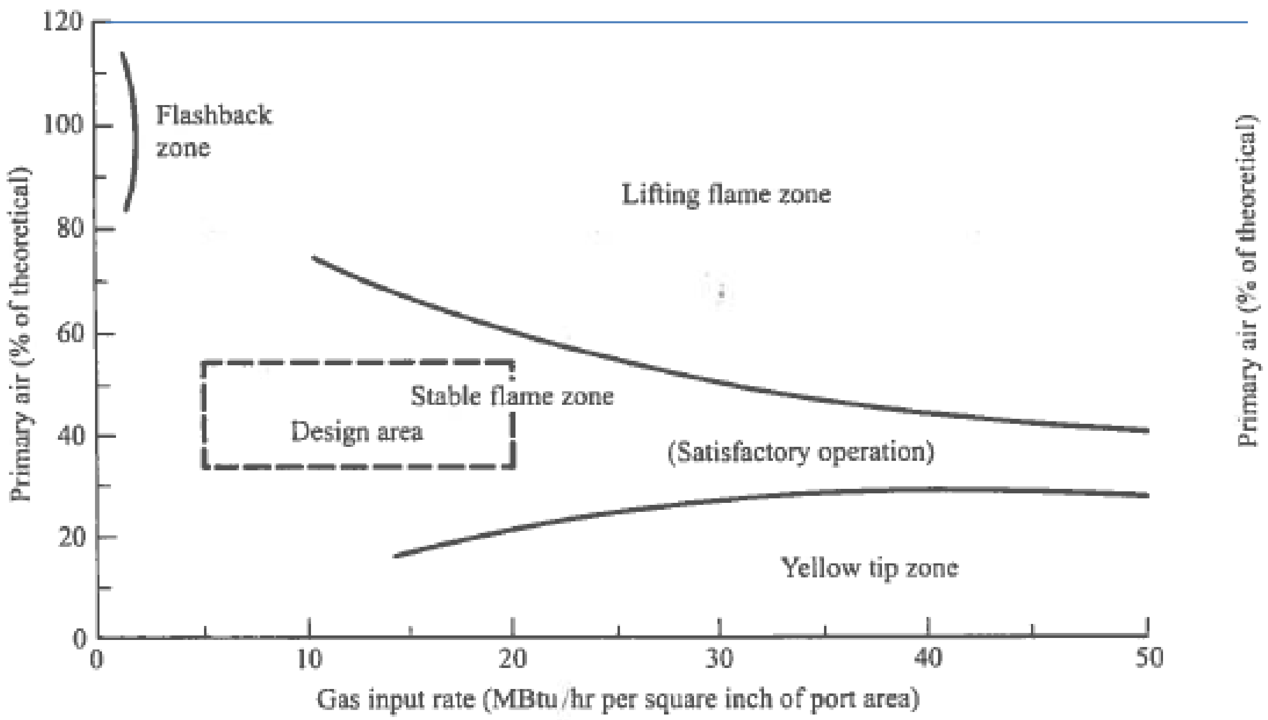
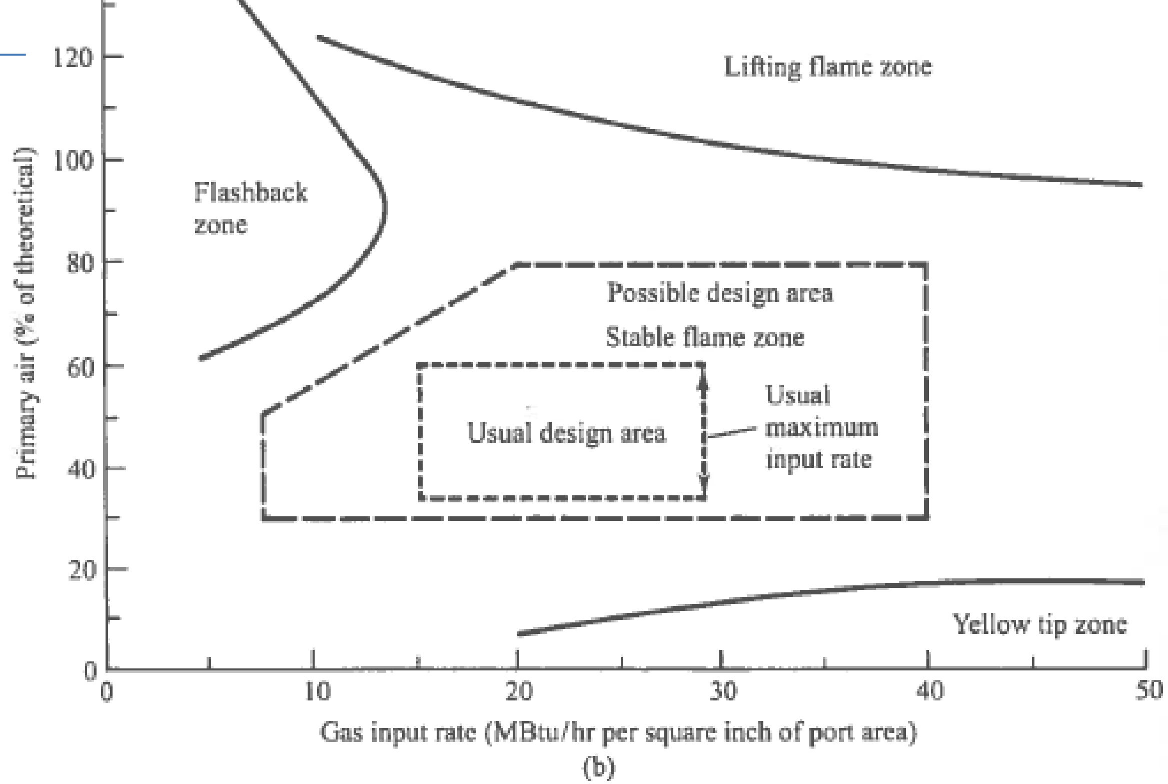
# “$H_2$ 101” - Fundamentals

- **Operability impacts**
  - **Presence of hydrogen leads to much wider operating limits but with high flashback risk**

Natural Gas




Syngas (H2/CO mixture)




**Source: Weber and Vandaveer, Gas Burner Design, 1965**



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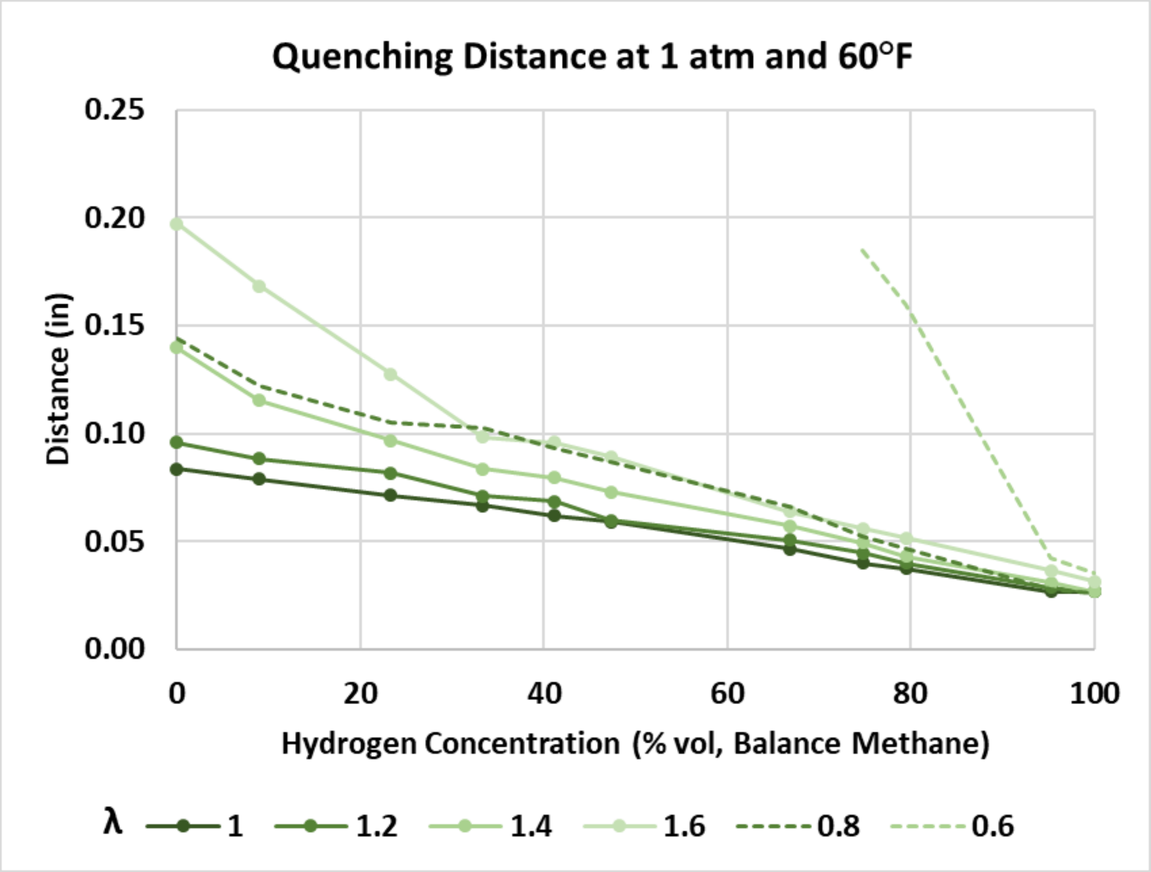
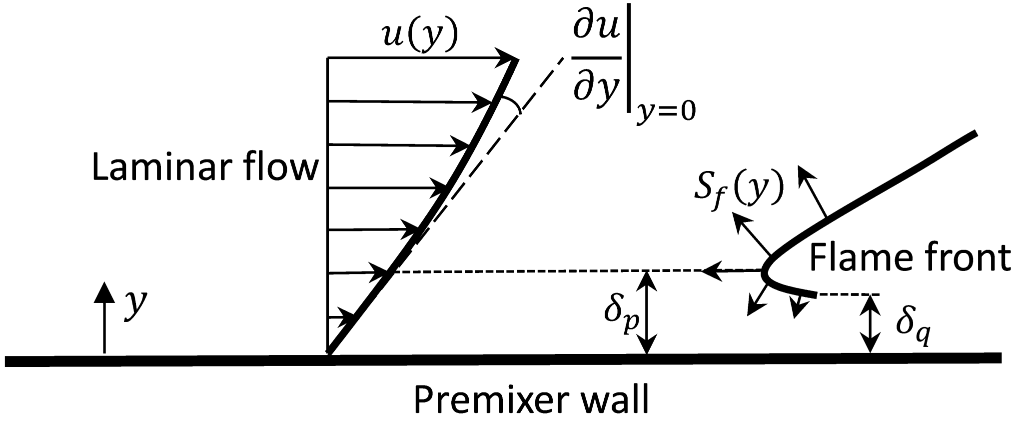
# “$H_2$ 101” - Fundamentals

- **Quenching Distance**




Source: GTI Energy




Source: Kalantari and McDonell (2017). Prog Enegy Combustion Sci., vol 61, 249

Hydrogen flame can exist much closer to the wall, thus allowing propagation upstream in the boundary layer

Implications for burner holes/mesh, etc



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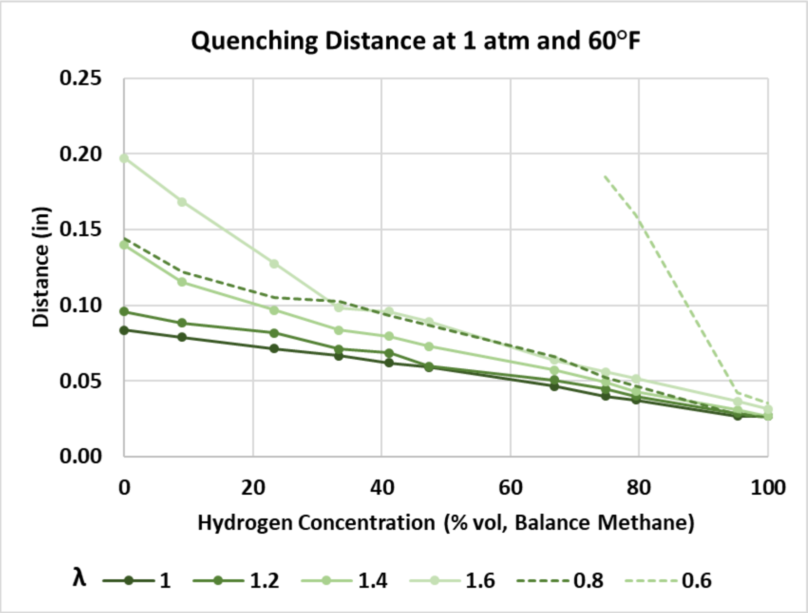
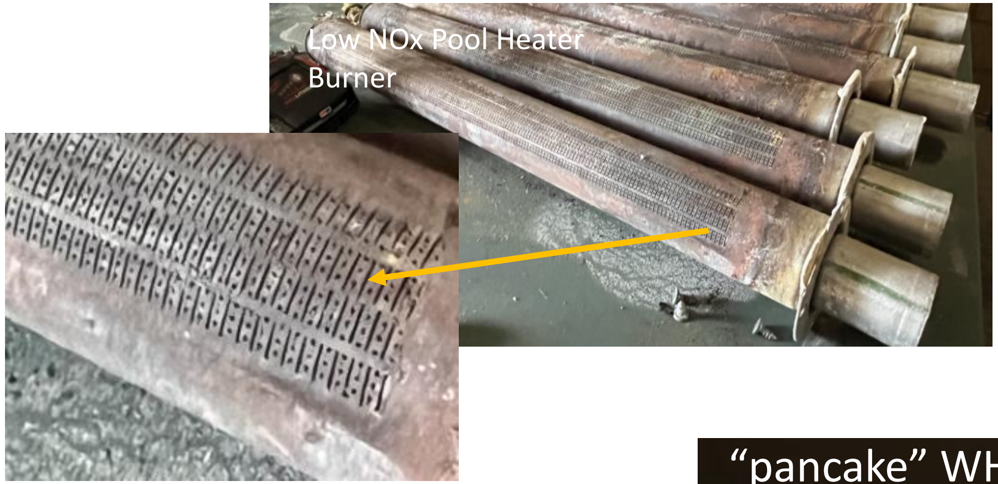
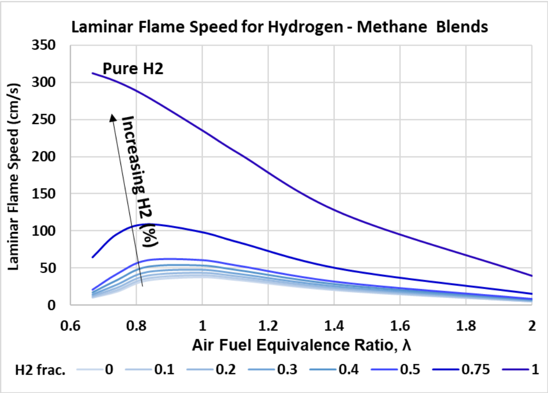
# "$H_2$ 101" - Fundamentals

- **For premixed burners, the small quench distance* poses special challenges for hydrogen**
  - **If flame is not quenched at a port—it will readily propagate (high flame speed)**

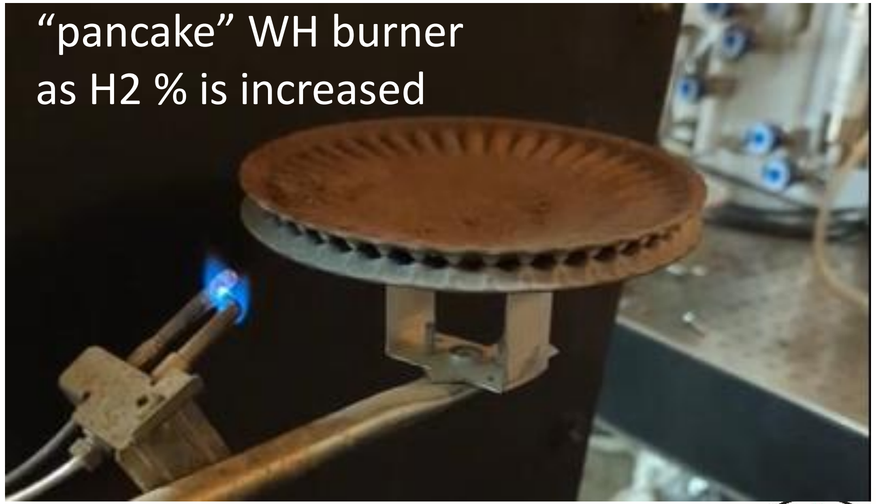



Source: GTI Energy




Source: GTI Energy




Source: UC Irvine

*Think about burner mesh/ports, etc



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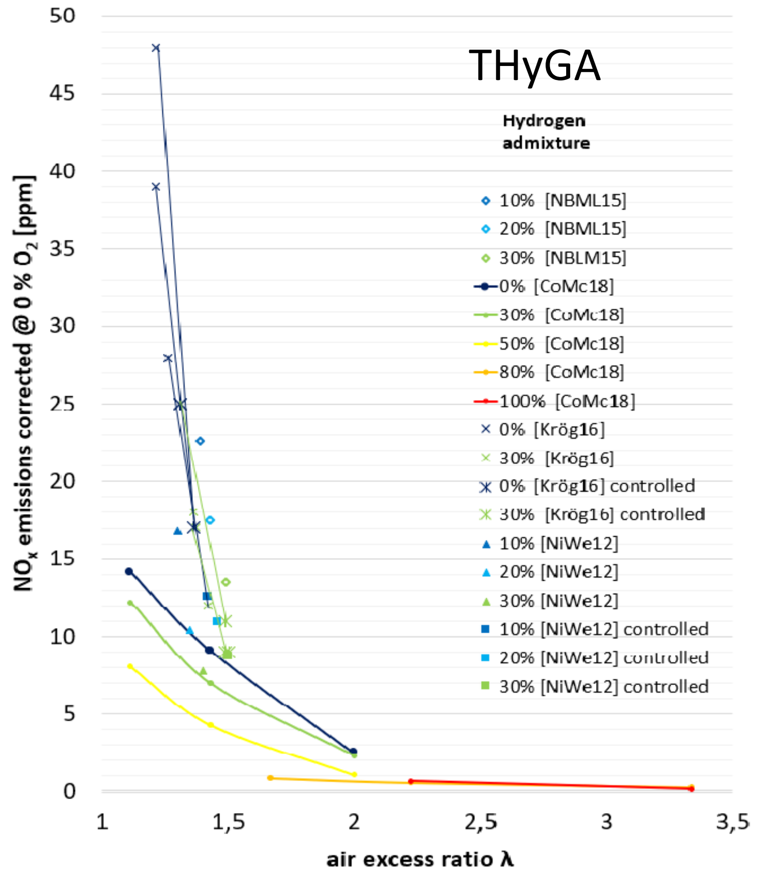
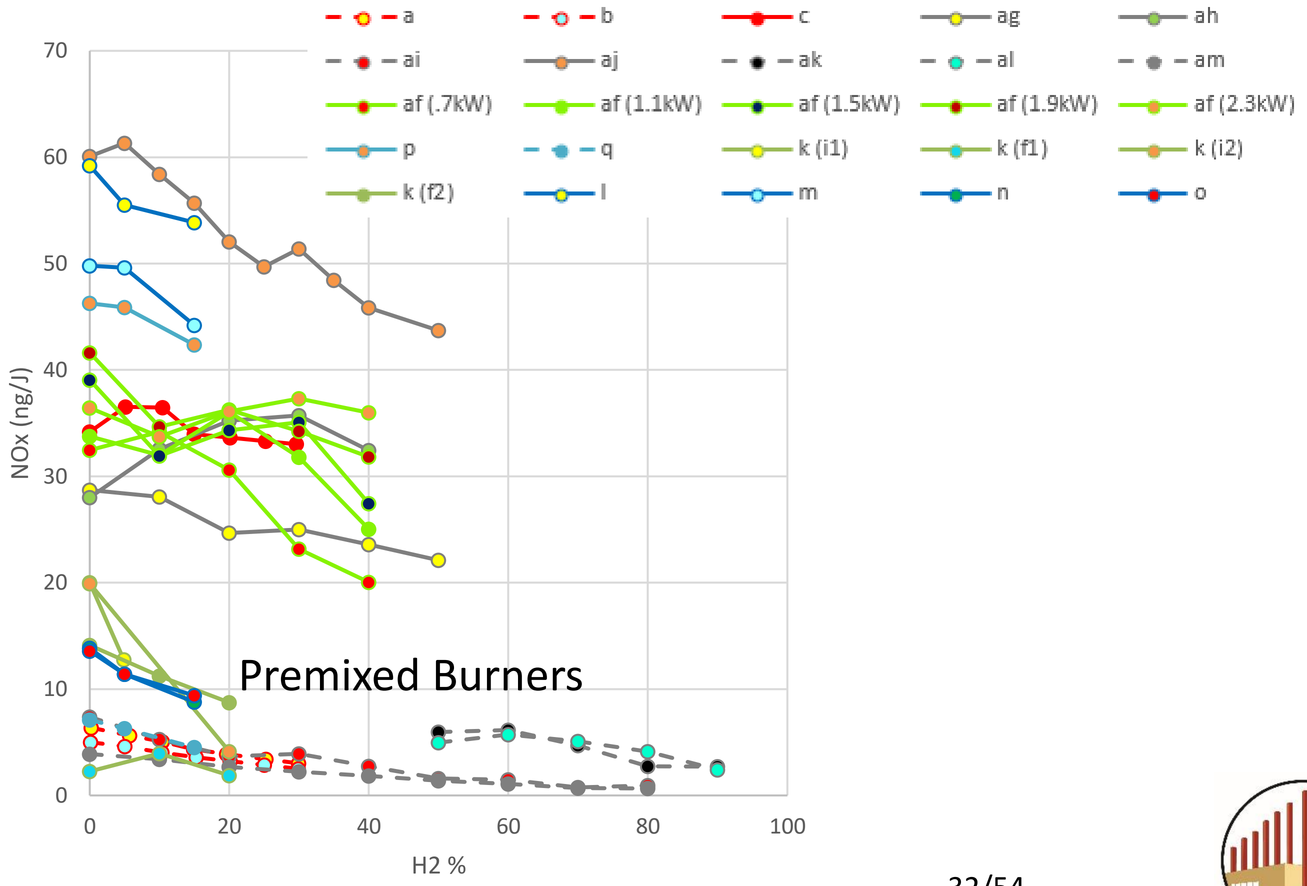
# “$H_2$ 101” - Fundamentals

- For <u>premixed burners</u>, NOx emissions will generally go down
  - Despite higher flame temperature for a given Lambda, because hydrogen needs less air to react, for a given air flow (e.g., entrained volume, forced volume), the operating temperature decreases because lamba inherently increases




Source: Basinger, Hickey and McDonell (2023). Int. J. Hydr. Energy Vol 48, 19733



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# "$H_2$ 101" - Fundamentals

- **Takeaways**
  - Hydrogen differs from natural gas
  - Flame luminosity
  - Flame speed
  - Flame temperature
  - Wider flammability limits
  - Up to some limit of H2, the fuels behave close enough that modifications not required
    - ✓ (~20-30%)?
      - – Limits have been driven by what is being done and is supported by combustion science
    - ✓ Current project is focusing on establishing the upper limit
    - ✓ Transition point from blend to pure hydrogen?



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# Examining the Effects of Hydrogen in End-use Appliances for Large Commercial Buildings and Industrial Appliances: Test Plan for Long-term Materials Impact



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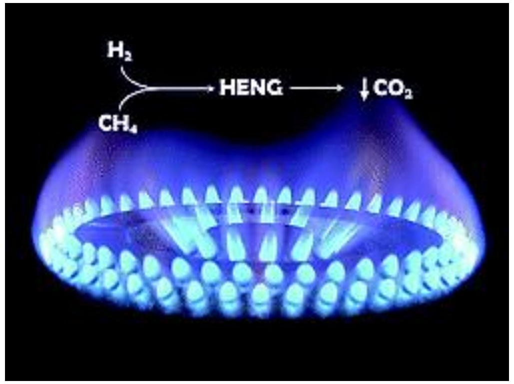
# What are concerns from a materials standpoint when burning $H_2$ in industrial appliances ?




Concerns can be divided to:

**1-** Pre-combustion

**2-** Post-combustion

- Pre-combustion Concerns: there are potential issues with H2 embrittlement and diffusion into structural materials at higher temperature (<550°C) in the combustor.

- Post-combustion concern: There is increased water vapor in the exhaust gas and the potential impact on hot section and downstream components.

Research at UCI will focus on post-combustion concerns from materials standpoint

# Post-combustion Environment

$H_2$ combustion products are different than those from carbon-based fuels. This results in a change in the exhaust gas composition, **such as higher water content.**

| | Reactants | | Products | | Reactants | | Products | | Reactants | | Products | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ϕ** | **$CH_4$ %** | **$H_2$ %** | **$H_2O$%** | **$O_2$%** | **$CH_4$ %** | **$H_2$ %** | **$H_2O$%** | **$O_2$%** | **$CH_4$ %** | **$H_2$ %** | **$H_2O$%** | **$O_2$%** |
| 0.95 | 100 | 0 | 18.15 | 0.96 | 50 | 50 | 21.39 | 0.94 | 0 | 100 | 33.27 | 0.88 |
| 0.74 | 100 | 0 | 14.42 | 5.07 | 50 | 50 | 17.06 | 5 | 0 | 100 | 26.91 | 4.73 |
| 0.50 | 100 | 0 | 9.98 | 9.98 | 50 | 50 | 11.86 | 9.88 | 0 | 100 | 19.01 | 9.51 |

- Exposing materials to exhaust gases with higher water content, altered composition, and increased temperatures can impact their long-term durability.
- Testing the effects of hydrogen ($H_2$) on material performance and developing strategies to improve durability is essential before setting safe $H_2$ addition limits.

# Project Objective & Test Methodology

**Objective:**

- Investigate the effect of blending natural gas with hydrogen ($H_2$) on the performance of materials used in commercial and industrial combustion systems.

**Tested Materials:**

- Focus on materials commonly used in industry, such as carbon steel, stainless steel and refractory materials such as alumina/silica.

**Testing Conditions:**

- Long-term tests ranging from a few hours to 100 hours.
- Temperatures representative of various industries (100 - 1650°C).

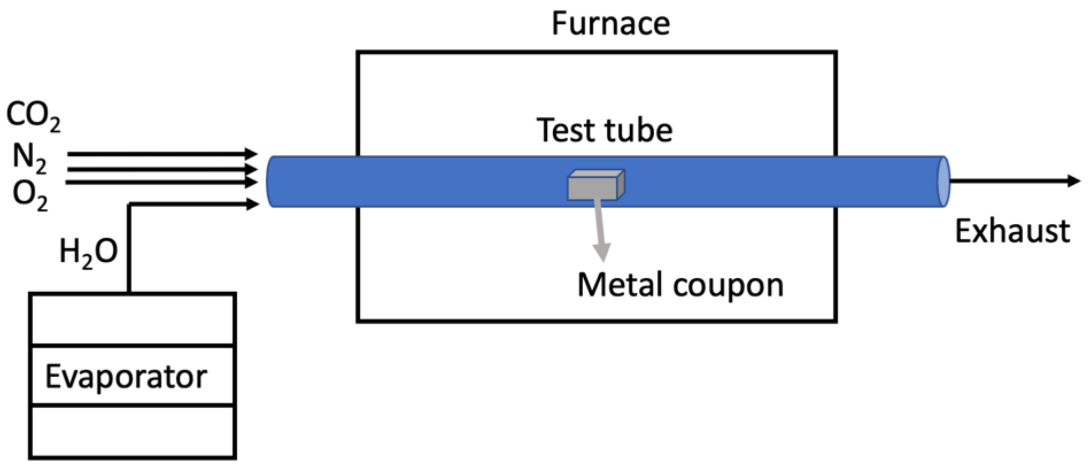
**Testing Methodology:**

- Coupons of different metals will be exposed to simulated exhaust environments.
- Exhaust composition will vary, focusing on water vapor content to simulate combustion of natural gas and $H_2$ blends (0 to 100% $H_2$).

# Materials used for different applications

| Industry | Burner | | Process/Furnace | | Exhaust | |
|---|---|---|---|---|---|---|
| | Materials | Temperature | Materials | Temperature | Materials | Temperature |
| **Glass** | Cast iron, low or medium carbon steel, SS – 316, Alloys | 50-250F (10-121°C) | Refractory – AZS | 2000-3000F (1093-1649°C) | Refractory | 1200-2000F (649-1093°C) |
| | Refractory | 70-3000 F (21-1648°C) | | | Carbon Steel | 500-1000F (260-538°C) |
| | | | | | Fabric | 200-400 F (93-204°C) |
| **Asphalt** | Refractory | 2500-3000F (1371-1649°C) | Refractory | | | |
| | low or medium carbon Steel | 50 - 250 F (10-121°C) | | | | |
| **Iron & Steel – High Temp.** | Cast iron, low or medium carbon steel, SS – 316, Alloys | 50-250 F (10-121°C) | Refractory – Alumina-Silica | 2000-2500F (1093-1371°C) | Refractory | 750-2000F (399-1093°C) |
| | Refractory | 70-2500 F (21-1371°C) | | | | |
| **Iron & Steel – Mid Temp.** | Cast iron, low or medium carbon steel, SS – 316, Alloys | 50-250 F (10-121°C) | Refractory | 1200-1800F (649-982°C) | Carbon Steel | 500-1000F (260-538°C) |
| | Refractory | 70-500 F (21-1371°C) | Fiberboard | 1200-1800F (649-982°C) | Alloy | 500-1500F (260-538°C) |
| | | | Alloy | 1200-2000F (649-1093°C) | | |
| | | | Ceramic – Si-SiC | 1500-2300F (816-1260C°) | | |
| **Food and Beverage** | low or medium carbon Steel | 70-1000F (21-538°C) | Carbon Steel | 400-500F (204-260°C) | Carbon Steel | 400-500F (204-260°C) |
| | Ceramics | | | | | |
| | SS – 304, 316 | | | | | |
| **Chemicals – Catalytic Cracking** | Cast iron, low or medium carbon steel, SS – 316, Alloys - | 50-250F (10-121°C) | | 900F (482°C) | Carbon Steel | 400-500F (204-260°C) |
| | Refractory | 70-2500F (21-1371°C) | | | Refractory | 750-2000F (399-1093°C) |
| **Refining** | | 2000F (1093°C) | 25Cr-35Ni | 1550F (843°C) | | 1000-1350F (538-732°C) |
| **Paper and Pulp – Boilers mainly** | Boilers | 2500F (1371°C) | Carbon steel, cast components | 120-350F (49-177°C) | High grade carbon steel | 200F (93°C) |
| **Cement** | Carbon Steel | 50-250F (10-121°C) | Refractory | 2000-3000F (1093-1649°C) | Refractory | 500-2000F (260-1093°C) |
| | Refractory | 2000-3000F (1093-1649°C) | | | | |

# Experimental Set-up




**Experimental Set-up:**

- Metal coupons will be heated in a test tube using a Thermcraft split furnace, with temperatures up to 1650°C to simulate high-temperature burner conditions.
- Exhaust gas will be composed of controlled mixtures of $CO_2$, $O_2$, $N_2$, and water vapor.
- Water vapor content will be adjusted to simulate exhausts of natural gas/$H_2$ blends.

**Safety Features:**

- Gas sensors in the walk-in hood detect leaks and activate a control panel that Shuts down gas supply from tanks, increases room ventilation,  triggers visual and audible alarms.

# Materials Characterization

**Characterization Facility:**

- Materials characterization will be conducted at UCI's Irvine Materials Research Institute (IMRI), equipped with advanced instrumentation for materials analysis.

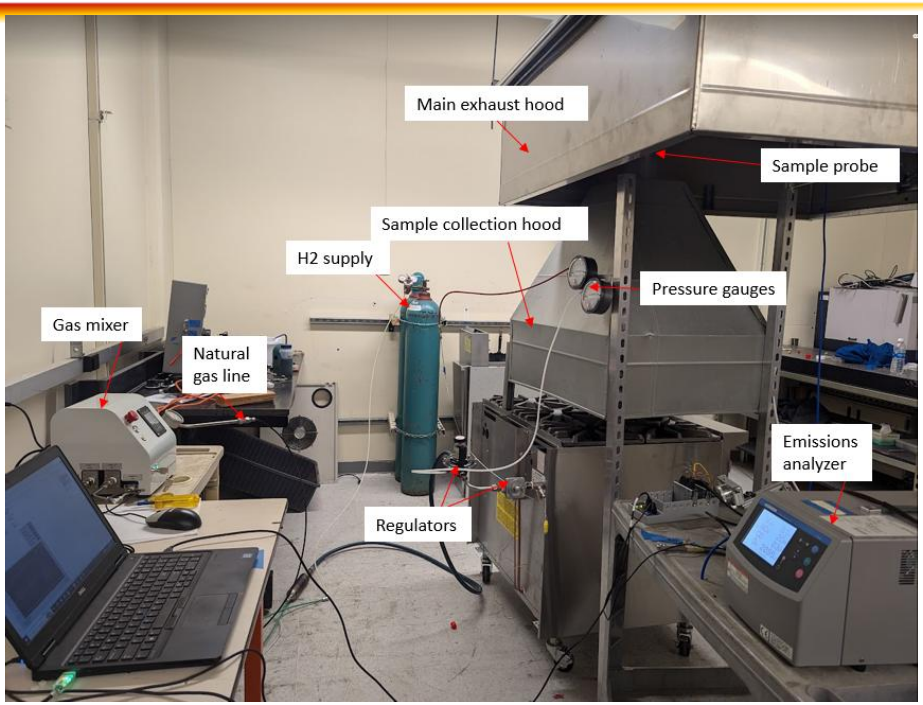
**Characterization Techniques:**

- **XRD:** Analyze changes in the crystal structure.
- **SEM:** Observe material structures and detect cracks, supported by elemental mapping with EDS.
- **FIB:** Prepare cross-sections of samples.
- **STEM:** Image cross-sections with EDS mapping for detailed elemental analysis.

**Objective:**

- These techniques will assess the impact of exhaust gases from natural gas/$H_2$ blends on material properties.

# Combustion Performance:  Devices Under Study





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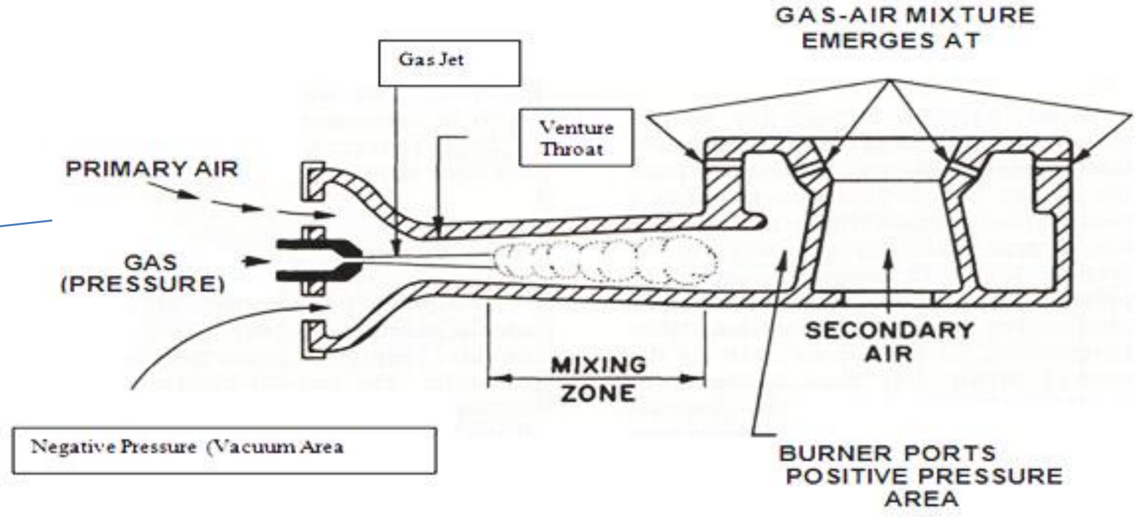
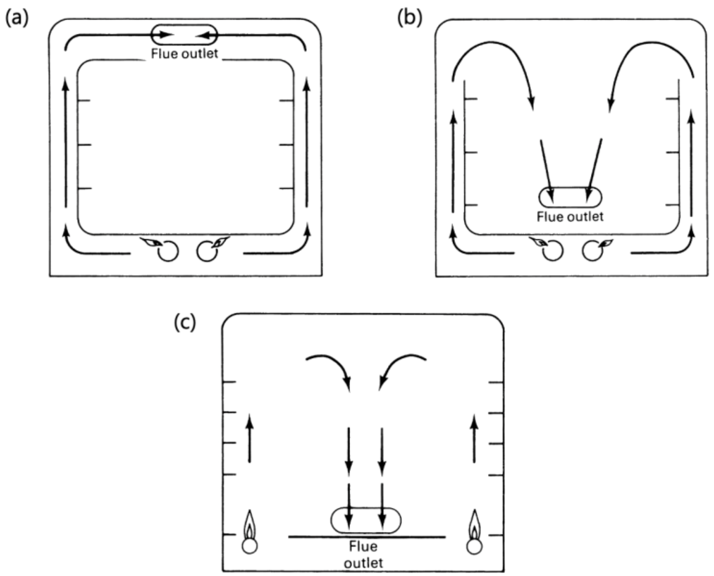
# Performance Testing Example:  Cooking Ranges

- **Stovetop/Range**

Cooking Ranges/Ovens



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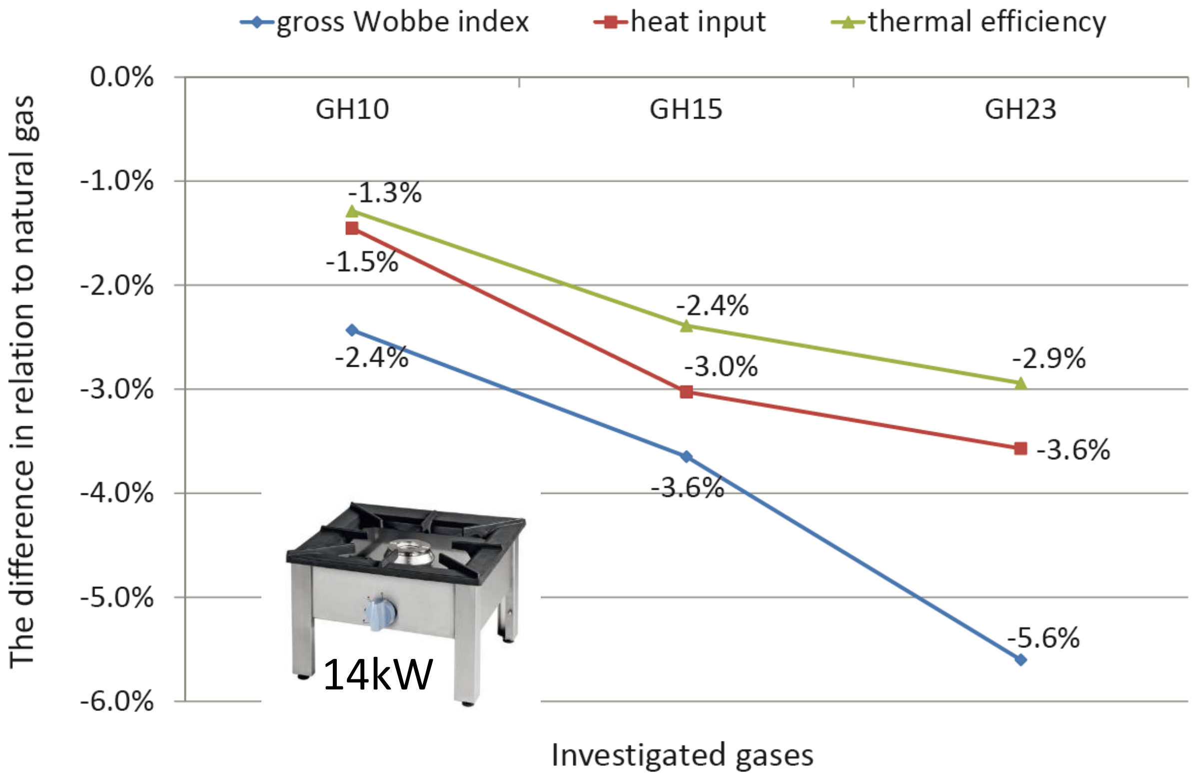
# Ranges

- **Previous Work: Gas Ranges**
  - **Commercial cooking stock pot range (Wojowicz, 2019)**
  - **Up to 23% hydrogen added**

| Parameter | | Unit | Gas symbols and parameter's value | | | |
|---|---|---|---|---|---|---|
| | | | 2E[*] | GH10 | GH15 | GH23 |
| Gas components | hydrogen | | – | 10.01 | 15.01 | 23.00 |
| | methane | % | 97.34 | 87.59 | 82.73 | 74.95 |
| | nitrogen | % | 1.15 | 1.04 | 0.98 | 0.89 |
| | others | % | 1.51 | 1.36 | 1.28 | 1.16 |
| Gross calorific value $H_S$ | | $MJ/m^3$ | 37.90 | 35.32 | 34.03 | 31.96 |
| Net calorific value $H_i$ | | $MJ/m^3$ | 34.17 | 31.78 | 30.58 | 28.66 |
| Gross Wobbe index $W_S$ | | $MJ/m^3$ | 50.16 | 48.94 | 48.33 | 47.35 |
| Net Wobbe index $W_i$ | | $MJ/m^3$ | 45.26 | 44.04 | 43.44 | 42.47 |
| Density $\rho$ | | $kg/m^3$ | 0.700 | 0.638 | 0.607 | 0.558 |
| Relative density $d$ | | – | 0.571 | 0.521 | 0.496 | 0.456 |



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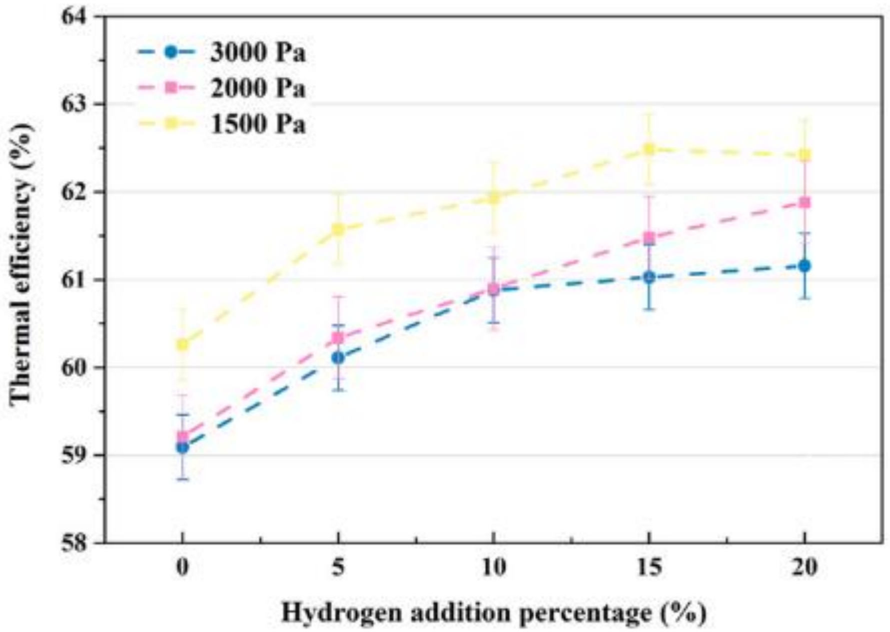
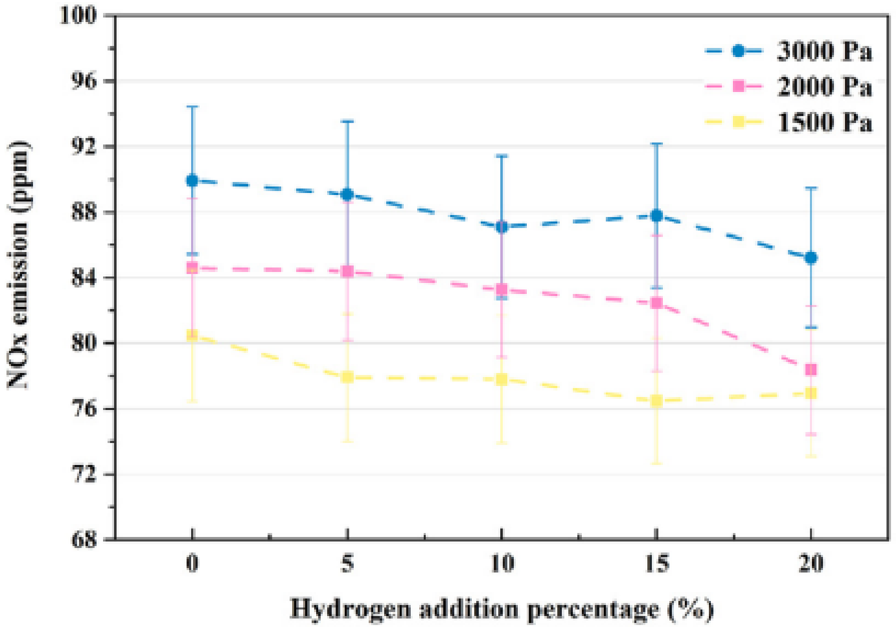
# Ranges

- **Previous Work: Sun et al., 2022—up to 20% hydrogen added by volume**
  - **Efficiency increases with hydrogen addition**
  - **NOx emission generally decrease**



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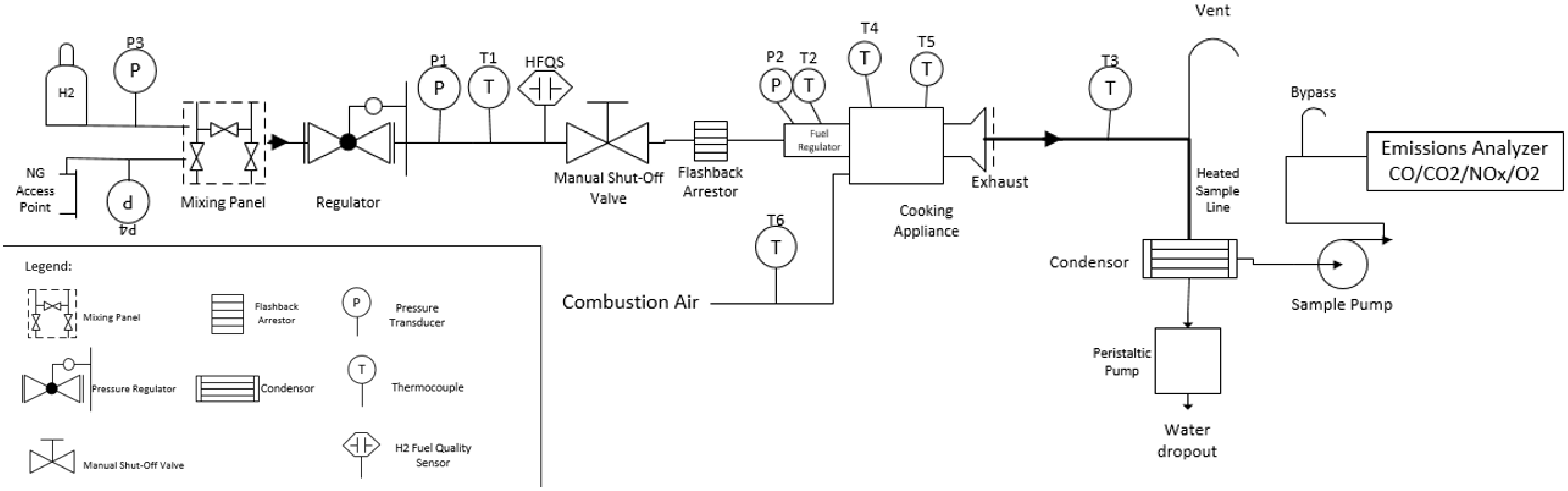
# Performance Results: Current Effort

- **Test Setup**



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# Performance Results: Current Effort

- **Test Plan**
  - Steady Combustion Test
  - Ignition Test
  - Dynamic Blending (“slug” test)
  - ASTM F1521-22 Efficiency Test

  - Base case with matched volume flow (dictated by maintaining gas pressure specs for fuel inlet)
    - ✓ Necessarily results in reduced heat input to device (Wobbe Index)
  - *If feasible*, matched heat input (requires override of controls, higher pressures, etc.)
    - ✓ This can be done via adjustments in metering and controls in the field if needed
    - ✓ If limited H2 addition (~20%) this can be done



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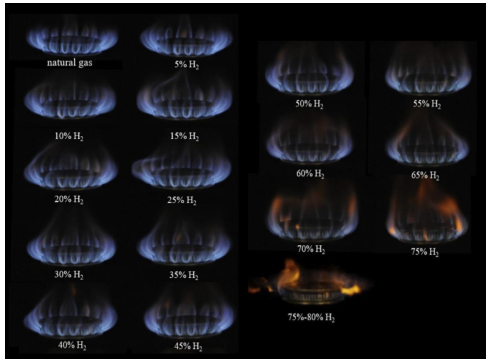
# Commercial Ranges

- **Ignition and Dynamic Blending Results**
  - **Commercial devices are tolerant to H2 addition**

| *Appliance* | *Heat Setting (High/low)* | *Flashback At (%$H_2$) Steady-state* | *Hot Cycle* | *Cold Cycle* | *Dynamic Blending Test (%$H_2$)* |
|---|---|---|---|---|---|
| Range 1 | low | 95 | NA | NA | 90 |
| | high | 90 | 90 | 70 | 80 |
| Range 2 | low | 90 | NA | NA | 80 |
| | high | 95 | 95 | 95 | 90 |

  - **Residential Systems exhibit issues at 45-50%**
    - ✓ **more tolerance if starting on NG and then increasing H2 content**




**Source: Zhao, McDonell, Samuelsen (2019). Int'l J Hydrogen Energy, Vol. 44(23), 12239**



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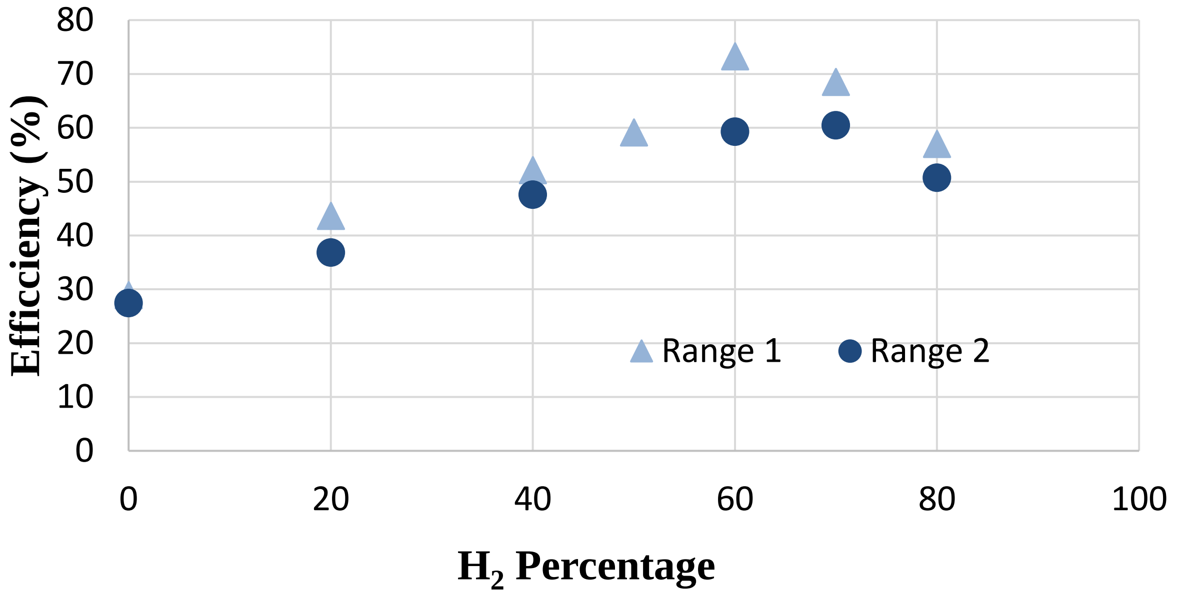
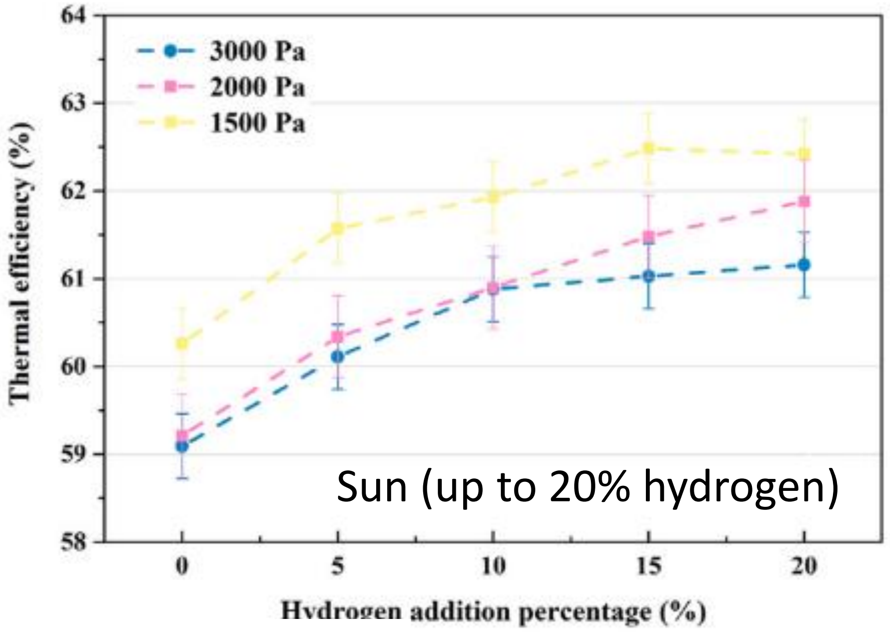
Preliminary Data – Subject to Change

# Commercial Ranges

- **Efficiency**
  - **ASTM F1521-22 Efficiency Test**




Sun (up to 20% hydrogen)

$$\eta_{cook} = \frac{E_{water} + E_{pot}}{E_{input}} \times 100\,\%$$

where:

$$E_{water} + E_{pot} = \left( \left( W_{water} \times Cp_{water} \right) + \left( W_{pot} \times Cp_{pot} \right) \right) \times \left( T_2 - T_1 \right)$$

$W_{water}$ = weight of water in the sauce pot, that is specified as 20 lb (9091 g) of water,

$Cp_{water}$ = specific heat of water = 1.0 Btu/lb·°F (418.7 J/kg·°K),

$W_{pot}$ = weight of cooking container, as specified in 6.3,

$Cp_{pot}$ = specific heat of cooking container, specified as either: aluminum = 0.22 Btu/lb·°F, or steel = 0.11 Btu/lb·°F,

$T_2$ = ending temperature of the water, that is specified as 200°F (93°C),

$T_1$ = beginning temperature of the water, that is specified as 70 ± 2°F (21 ± 1°C), and

$E_{input}$ = energy consumed by the cooking unit during the test, Btu, including any electric energy consumed by a gas range top.



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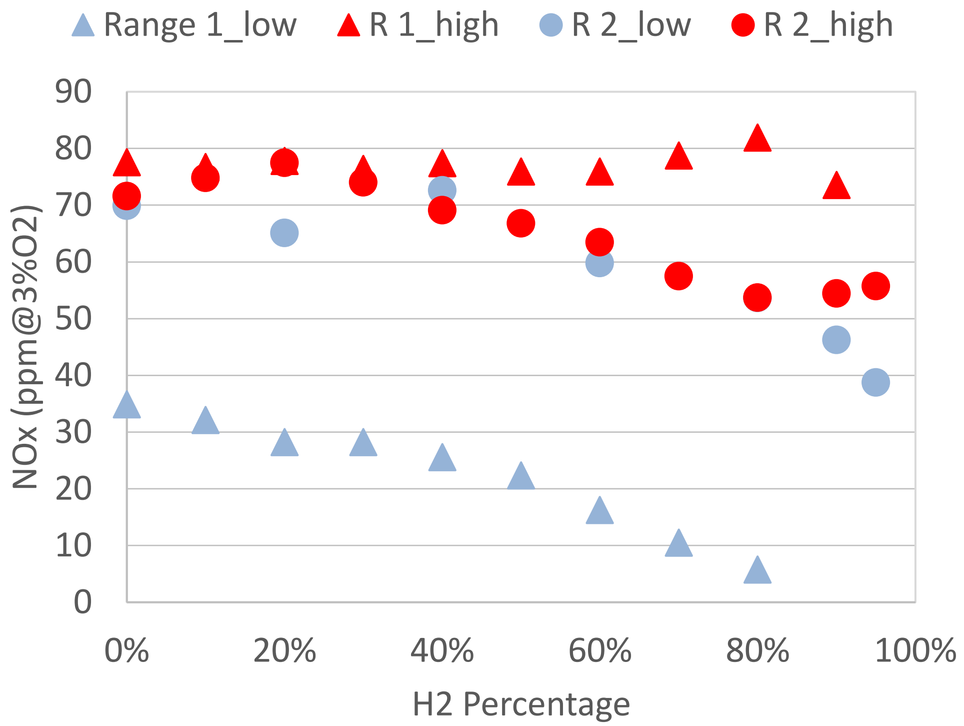
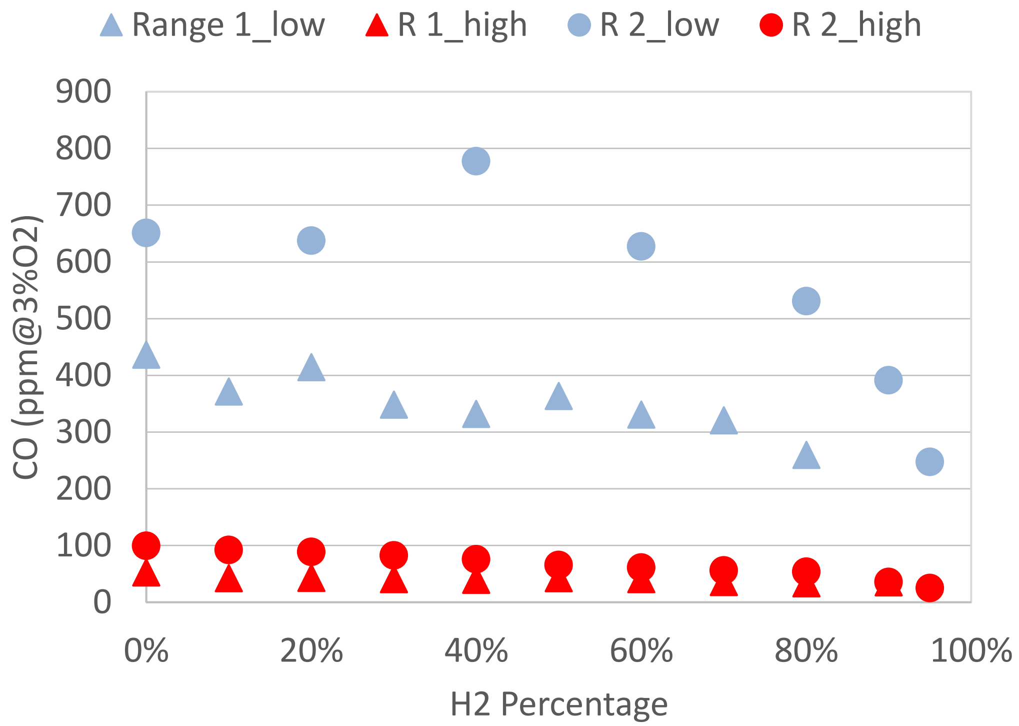
Preliminary Data – Subject to Change

# Commercial Ranges

- **Emissions**



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Preliminary Data – Subject to Change

# General Tolerance of Commercial Devices

- **Ranges, Ovens, Griddles, Fryer**
  - **Operability**

| Appliance | Heat Setting (High/low) | Flashback At (%H2) Steady-state | Hot Cycle | Cold Cycle | Slug Test |
|---|---|---|---|---|---|
| Range 1 | low | 95 | | | 90 |
| | high | 90 | 90 | 70 | 80 |
| Oven 1 | low | 95 | 90 | 90 | 90 |
| | high | 90 | 90 | 90 | 80, 85 |
| Range 2 | low | 90 | | | 80 |
| | high | 95 | 95 | 95 | 90 |
| Oven 2 | low | 95 | 90 | 70 | 90 |
| | high | 90 | 90 | 70 | 80 |
| Griddle 1 | low | 100 | | | 95 |
| | high | 95 | 95 | 90 | 90 |
| Griddle 2 | low | 80 | 80 | | 70 |
| | high | 70 | 70 | 70 | 60 |
| Fryer 1 | Low | 100 | 100 | 100 | 90 |

- In comparison to residential appliances the devices studied here have more tolerance to hydrogen addition



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Preliminary Data – Subject to Change

# Example of Flashback

- **Oven Burner "failure" mechanism**

Example of Flashback for Oven Burner

90-95% Hydrogen

UCI Combustion Laboratory

UCIrvine | University of California



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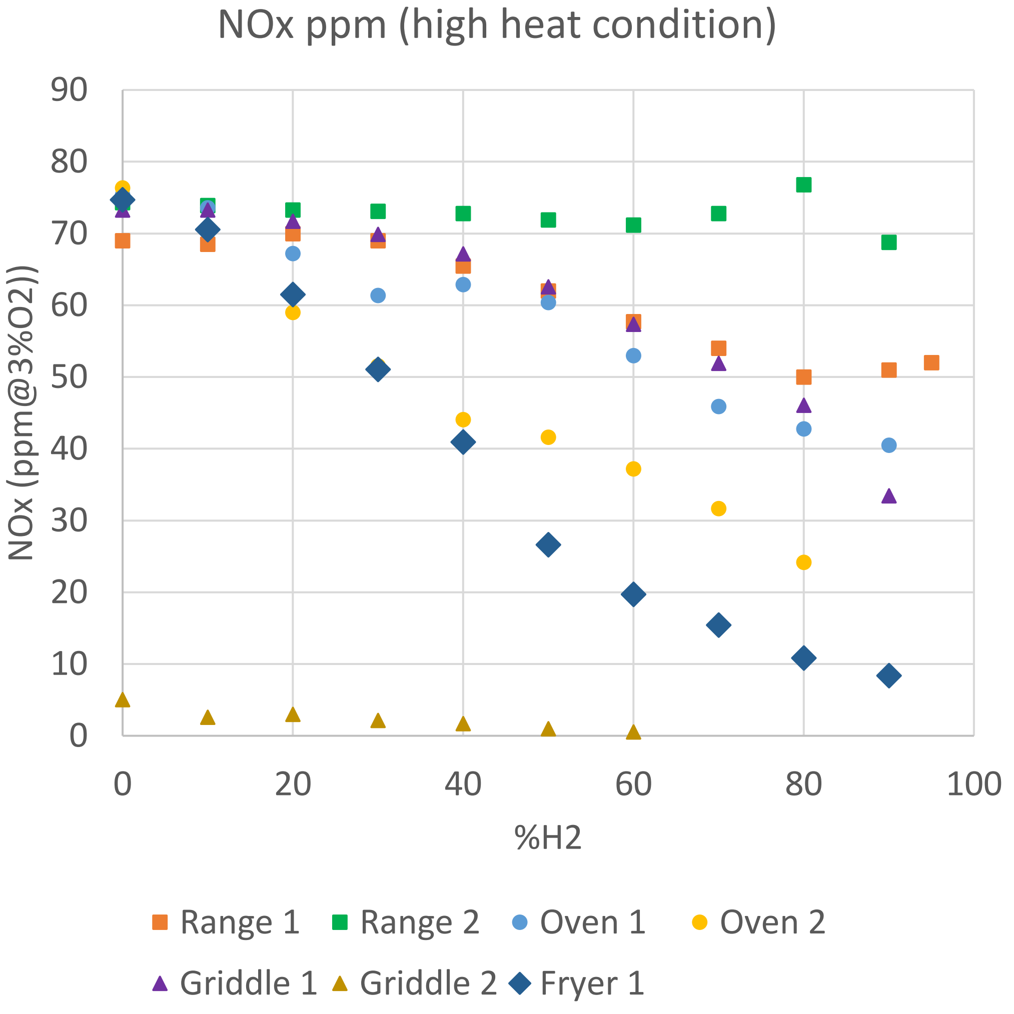
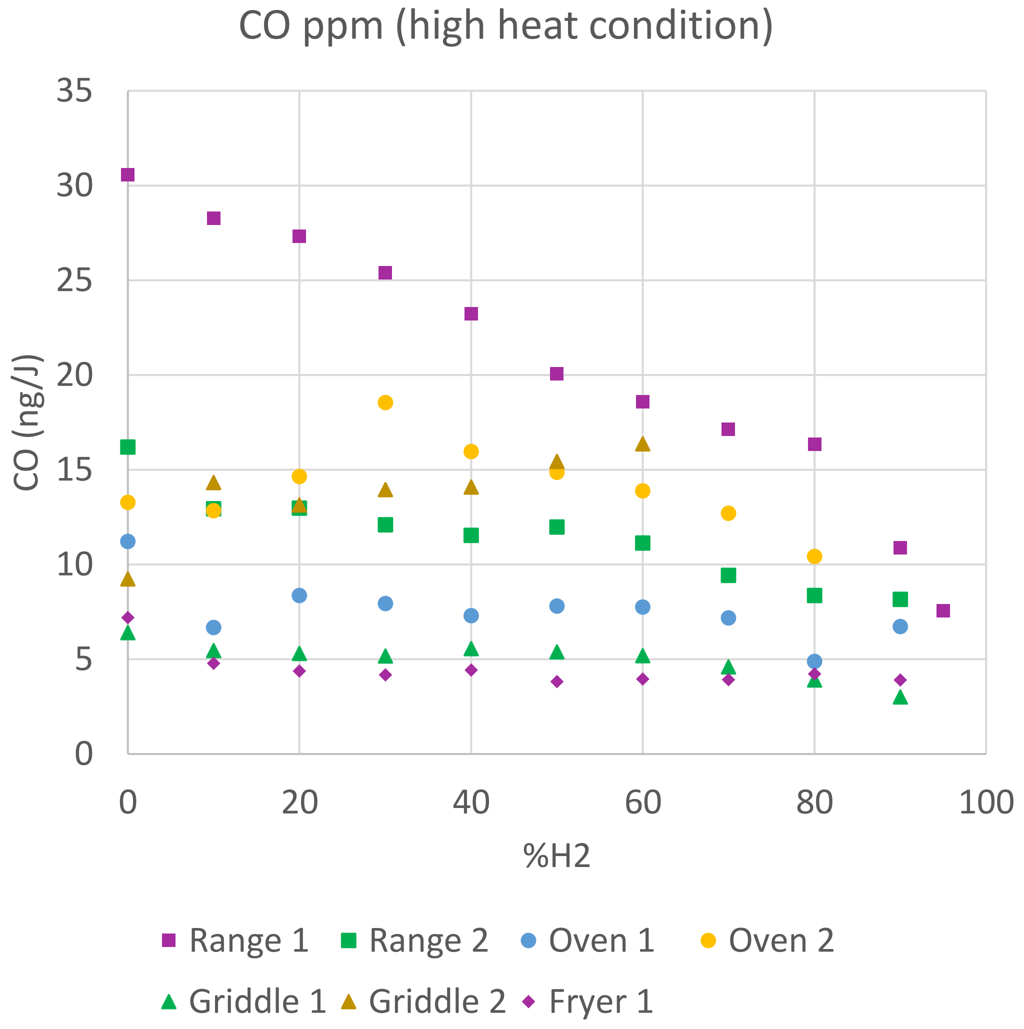
Preliminary Data – Subject to Change

# Summary of Emissions Performance for Cooking Appliances

- **Range, Oven, Griddle, Fryer**



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**Preliminary Data – Subject to Change**

# More to come.....





Planning to test Units
in UCI Combustion Lab






Water Heaters
Dryer Units

Cooking Units (Classroom)

Building Heater
Water Heaters

Pool Heating Units



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# Questions & Answers


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**Acknowledging our Project Partners and Funders:**


## Session #2 (3:00p-4:00p)

**Research Project Plan & Results – Cont. (GTI)**

- Review the experimental test plan and preliminary results for Industrial Combustion Equipment, Boilers, and Water Heaters

**Hydrogen – OEM Perspective (A.O. Smith)**

- Manufacturer perspective on $H_2$ applied to heating equipment and testing results

**Pulling it All Together – $H_2$ Big Picture (GTI)**

- Putting research data into broader context, including techno-economics, codes & standards, trends in test data, and $H_2$ safety