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solutions that transform

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Alex Fridlyand is Senior Engineer within the Building Energy Efficiency group at GT Energy. His research has focused on novel combustion system design, emerging HVAC&R equipment, as well as building energy modeling. He has over ten years of experience in applied and theoretical research in combustion, heat transfer, and thermodynamics. He has a Ph.D. in Mechanical Engineering from the University of Illinois at Chicago and a B.S. in Mechanical Engineering from the University of Illinois at Urbana-Champaign.

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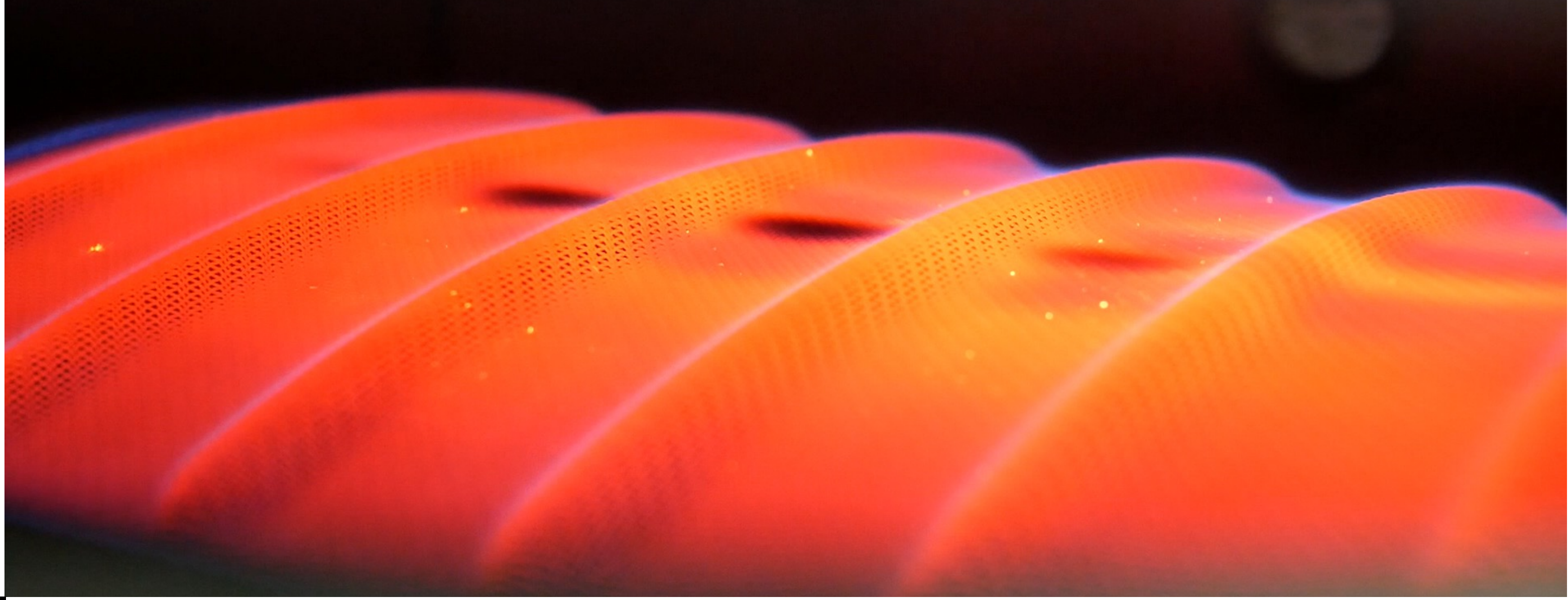


Introduction of Hydrogen to North American Appliances

Alex Fridlyand, Ph.D., *Senior Engineer*

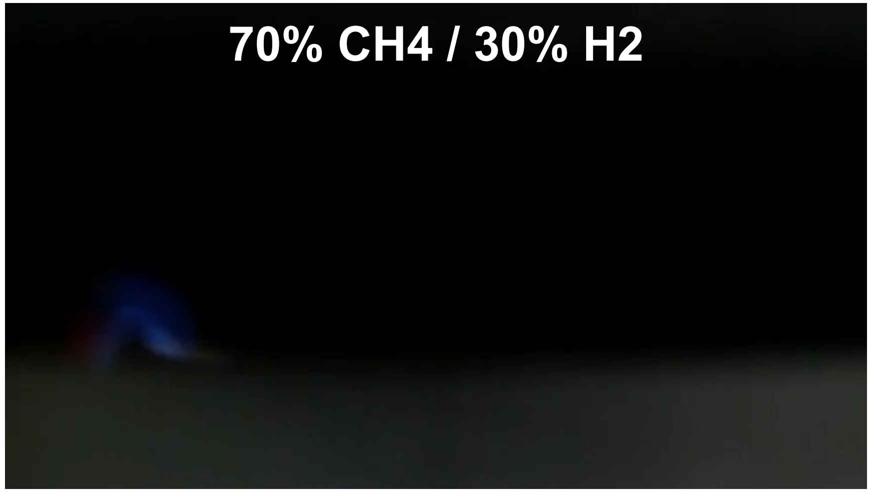
ASGE National Technical Conference| June 7th, 2022

Agenda

- Introduction to Decarbonized Fuels
- Hydrogen's Role in Decarbonizing Energy Systems
- Challenges and Opportunities with Hydrogen as a Fuel
- H2-Blending in Industry Today
- Snapshot of GTI's Work and Projects
  - Blending Tests
  - Burner Design Fundamentals

Energy Efficiency + Decarbonized Fuels

- **Energy efficiency** coupled with **decarbonized fuels** can drive GHG reductions
- As a fuel, Hydrogen (H2) emits no CO_2 and can be blended with natural gas or **biomethane** for standard products, or utilized directly (100% H2) by **specially-designed equipment**
  - Used for long duration, mega-scale storage of renewable

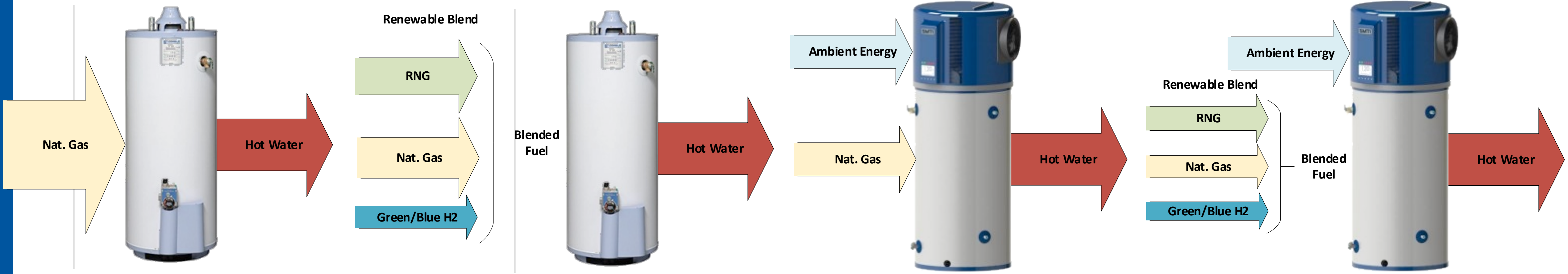


Baseline

Baseline + Decarb. Fuel*
~50% Fossil Reduction

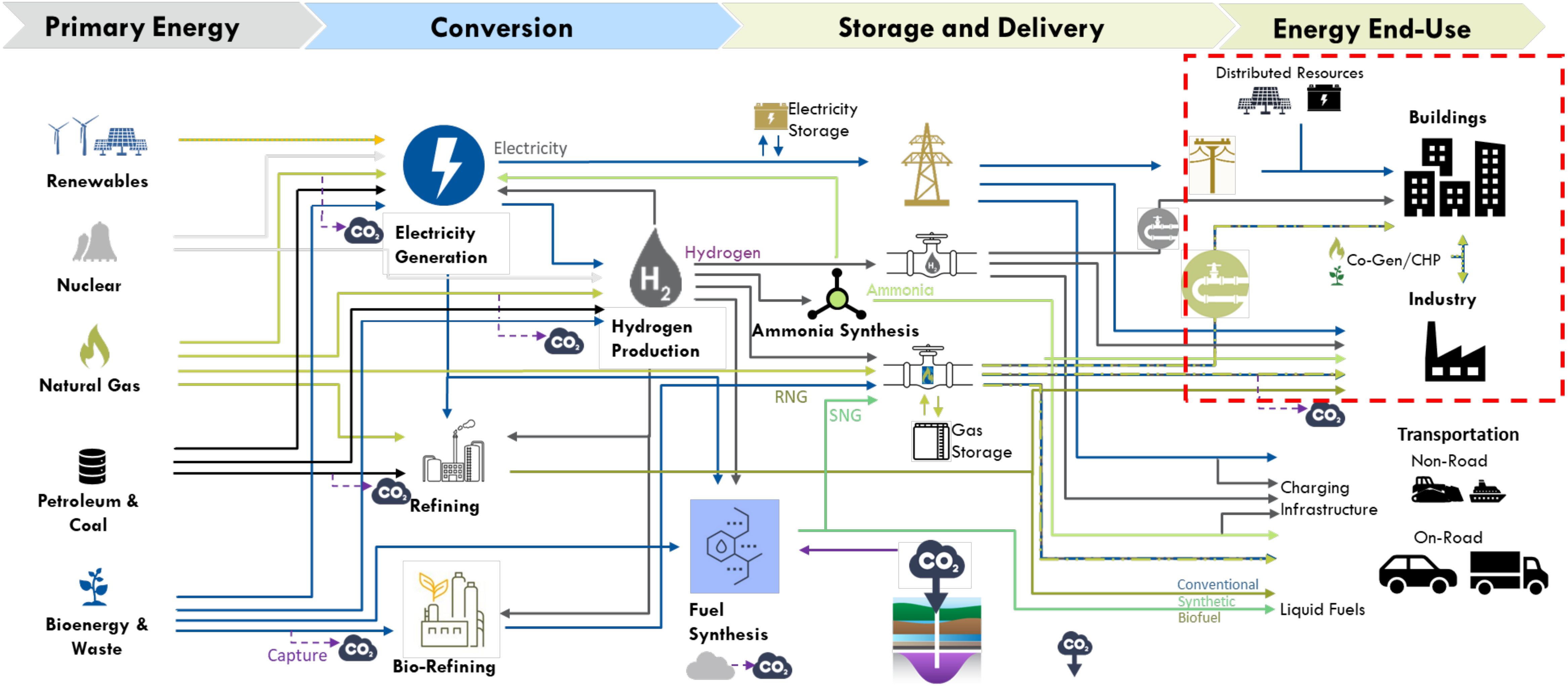
High-Efficiency**
~60% Fossil Reduction

High-Efficiency + Decarb. Fuel**
~80% Fossil Reduction



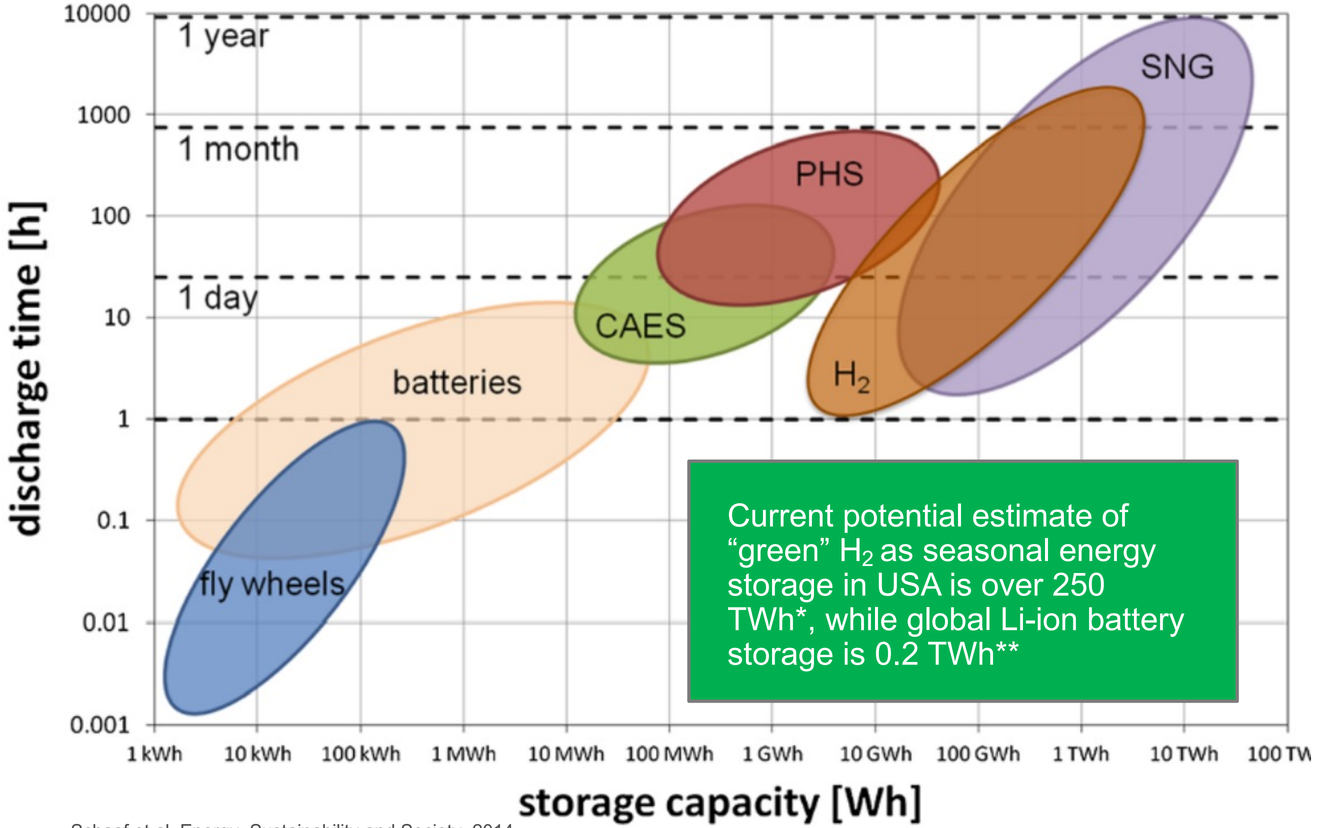
*Assumes near-term achievable targets of H2 & RNG blending / ** Fuel-fired GHPWH performance assumptions from *Glanville, P., Fridlyand, A., Mensinger, M., Sweeney, M., Keinath, C. (2020) Integrated Gas-fired Heat Pump Water Heaters for Homes: Results of Field Demonstrations and System Modeling, ASHRAE Transactions; Vol. 126 325-332,* image source: SMTI.

Hydrogen: Where Does It Fit In?

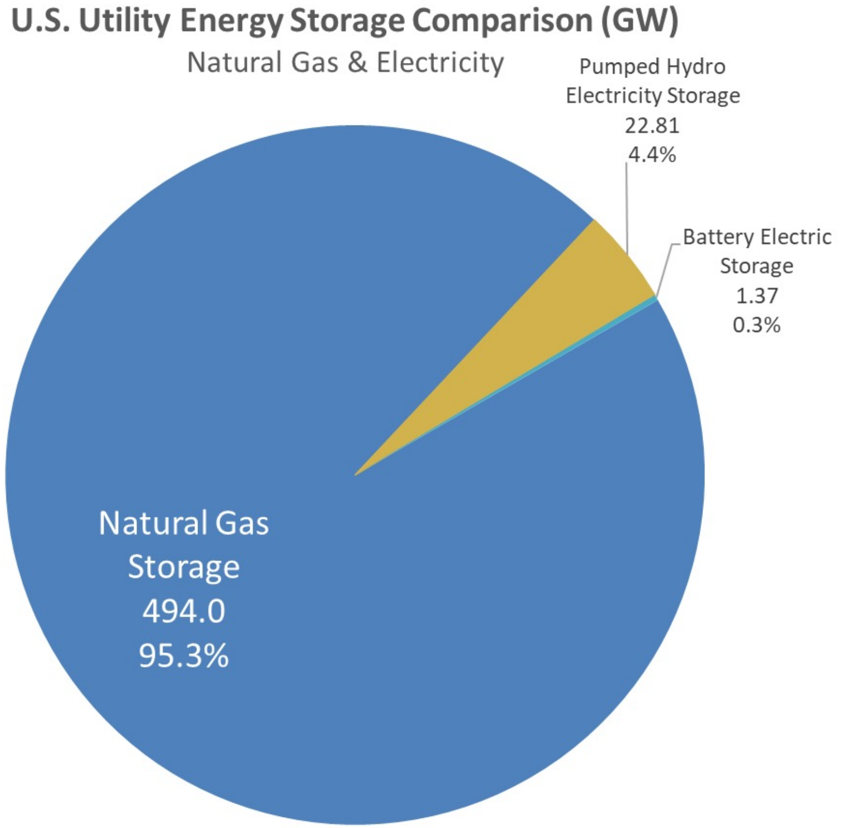


Hydrogen is envisioned to play an important role in economy-wide decarbonization, per the **Low-Carbon Resources Initiative** (LCRI), a five-year R&D effort to accelerate the deployment of low-carbon technologies, jointly led by **EPRI and GTI**.

Hydrogen: Where Does It Fit In?



Schaaf et al, Energy, Sustainability and Society, 2014, DOI 10.1186/s13705-014-0029-1.



Natural gas underground storage comprises >95% of U.S. utility energy storage capacity. During peak cold spells, gas storage can flex up to 600 GW of sustained energy delivery capacity for a week or more.

Sources: DOE-EIA /*NREL/TP-6A20-77610 (2020) / ** NREL/TP-5400-78461 (2020)

http://web.ecs.baylor.edu/faculty/grady/_13_EE392J_2_Spring11_AEP_Transmission_Facts.pdf

Decarbonization Potential of Delivered Hydrogen

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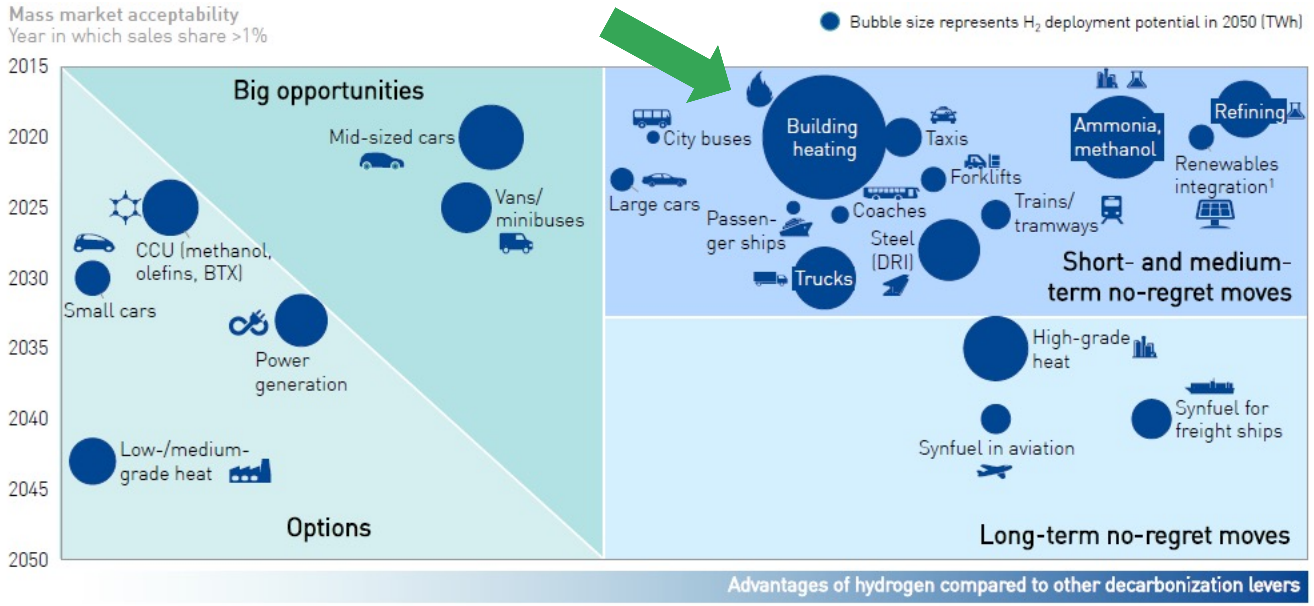
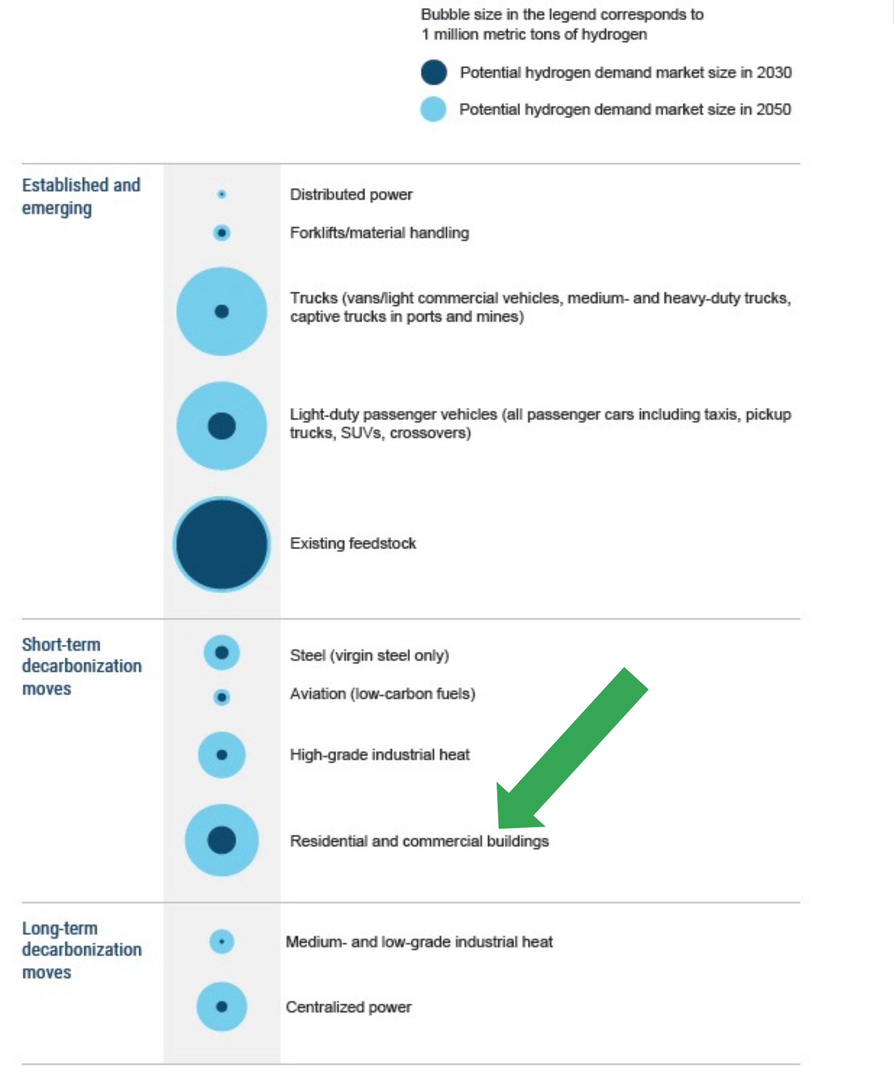
- **Feasibility:** Roadmaps emphasize near-term potential in buildings relative to other sectors
- **Scale-up:** With increasing scale (e.g. blend rates), delivered H2 stimulates increasing demand, driving down generation/storage costs



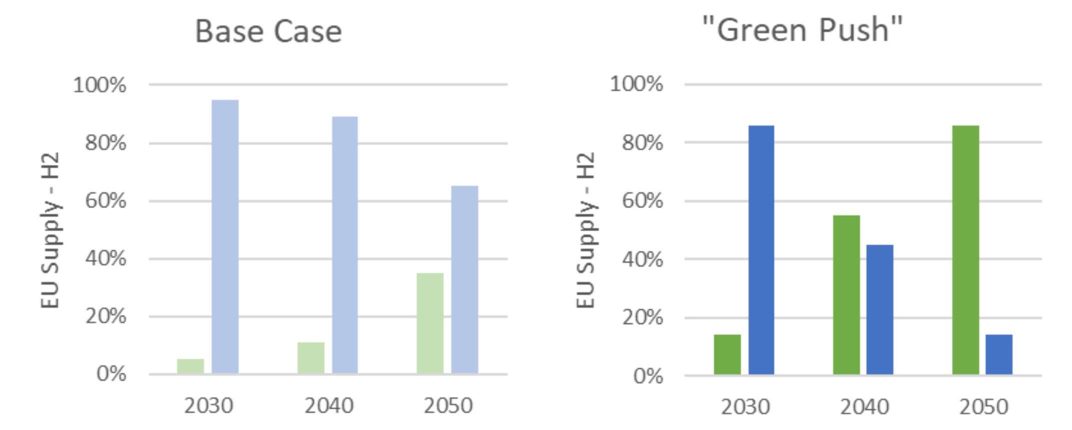
Source: Hydrogen Roadmap Europe, https://www.fch.europa.eu/news/hydrogen-roadmap-europe-sustainable-pathway-european-energy-transition



Source: FCHEA Hydrogen Roadmap (USA), https://www.fchea.org/us-hydrogen-study

The Many Colors of Hydrogen

- **Brown hydrogen** is generated by gasifying solid fuels, generally coal, without CO2 capture, less common in North America than Europe/Asia
- **Gray hydrogen** is produced with steam methane reforming (SMR), commonly with natural gas as a feedstock. ~71% of delivered hydrogen is Gray in Europe vs. ~95% in North America
- **Blue hydrogen** is gray hydrogen with integrated carbon capture and sequestration, generally viewed as a bridge to 2050
- **Green hydrogen** is generated by electrolysis, powered by excess renewable electricity or from other renewable resources**
- **Pink hydrogen** is generated by electrolysis powered by nuclear power plants



Blue hydrogen expected to play big role in EU near-term*

But many high-profile **green hydrogen** production facilities are planned using renewable electricity or waste streams**

*Source: Aurora Energy Research, 2020 / ** There is not global consensus on whether "green hydrogen" includes or excludes generation from renewable/waste solid feedstocks

Can we blend hydrogen with natural gas?

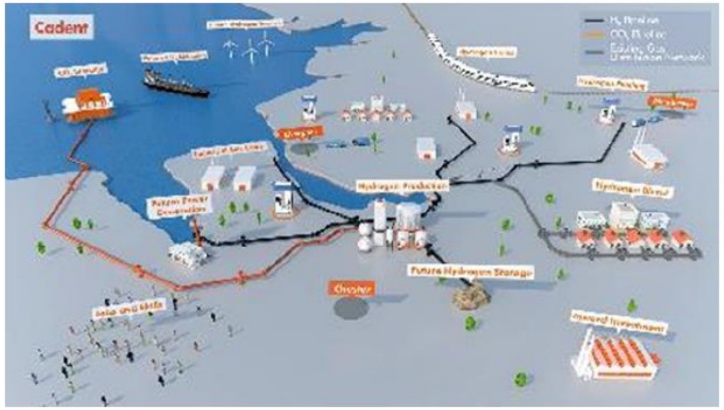
History Doesn't Repeat Itself, by it Rhymes…

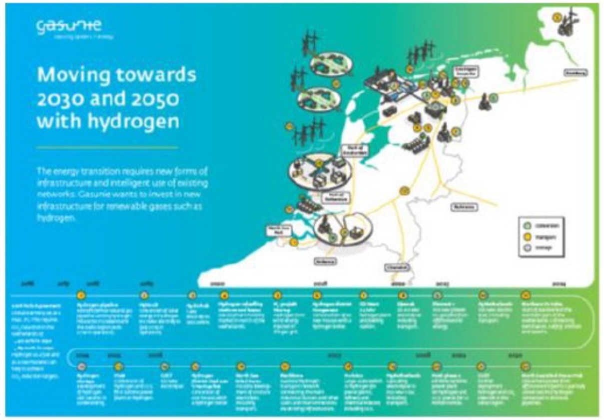
- Public gas distribution begins in US in 1816 (Baltimore)
  - Pine tar, then coal, then oil gasified in municipal gas plants, ~1000 US plants at peak (1890s)
  - Fuel typically syngas (H2/CO), "water gas" and "coal gas", Useful byproducts also sold (tars, cokes, etc.)
  - In 19th century, 90% of revenues were lighting, then expand into domestic/commercial (via leasing), then industrial uses
- Between WWI / WWII, pipeline advances & leak abatement bring "Natural Gas" to major urban centers
  - Majority began with "enriching" mfd. gases by blending (NG ~2X HHV) – NOLA (1928), Chicago (1931), Minneapolis (1935)
  - Others did straight conversion – DC (1946), NYC (1949-51)
  - Overall conversion took **30-40 years** in US, "single largest task" was converting customer equipment (utility-led or contractor)
- Legacy of mfg. gas transition remains in appliance design/codes

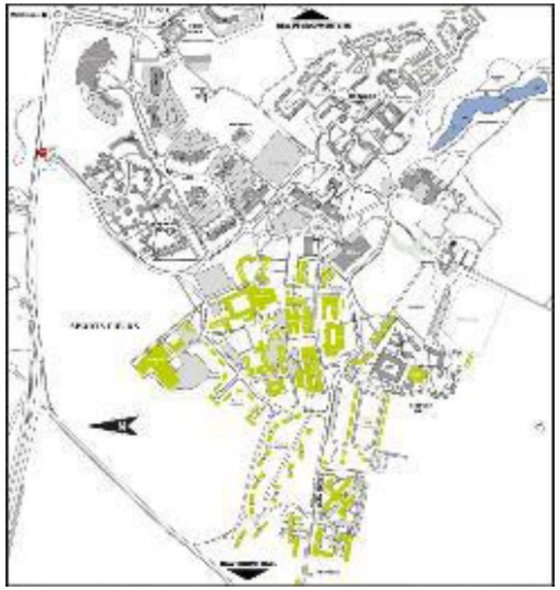
Source: Pacific Coast Gas Association – A Century of Progress - 1993

https://www.researchgate.net/publication/291164699_Transforming_an_Energy_System_The_evolution_of_the_manufactured_gas_industry_and_the_transition_to_natural_gas_in_the_US_1807-1954

Hydrogen Deployment Internationally





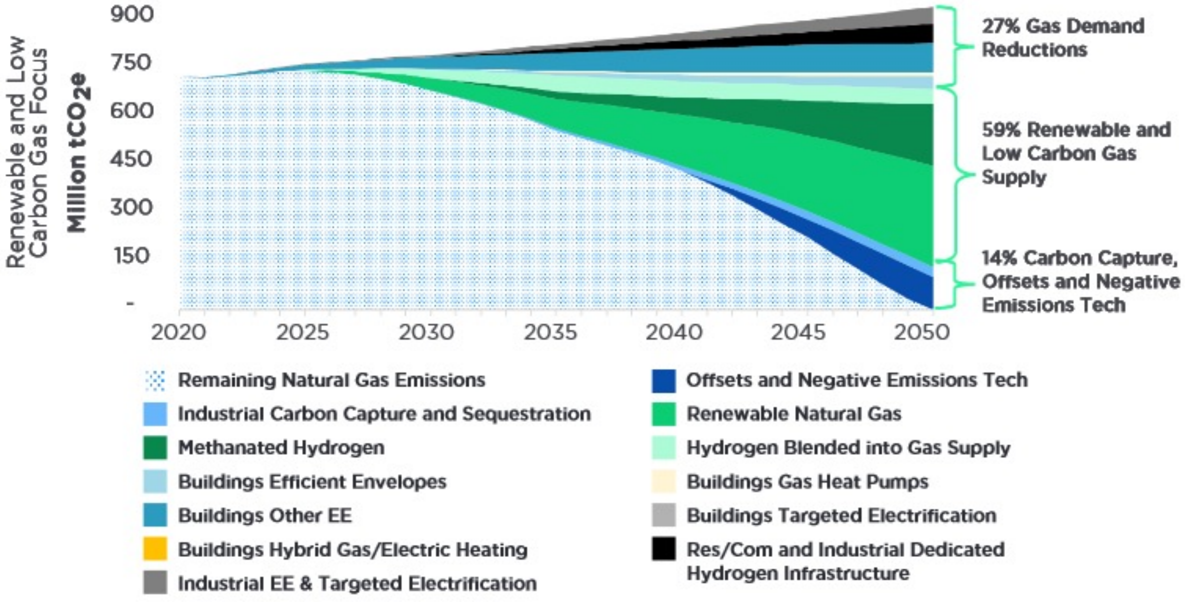


Deployed Projects Examples:

- H21 – UK
- HyNET – UK
- HyDeploy – UK
- HYPOS – Germany
- HySynGas – Germany
- Hybridge - Germany
- Crystal Brook Energy Park - Australia
- FH2R Toshiba Tohoku Iwatani – Japan
- H2-Powered Cities by 2022 – S. Korea
- HyNetherlands – H2 passenger train
- Many more in various stages of development

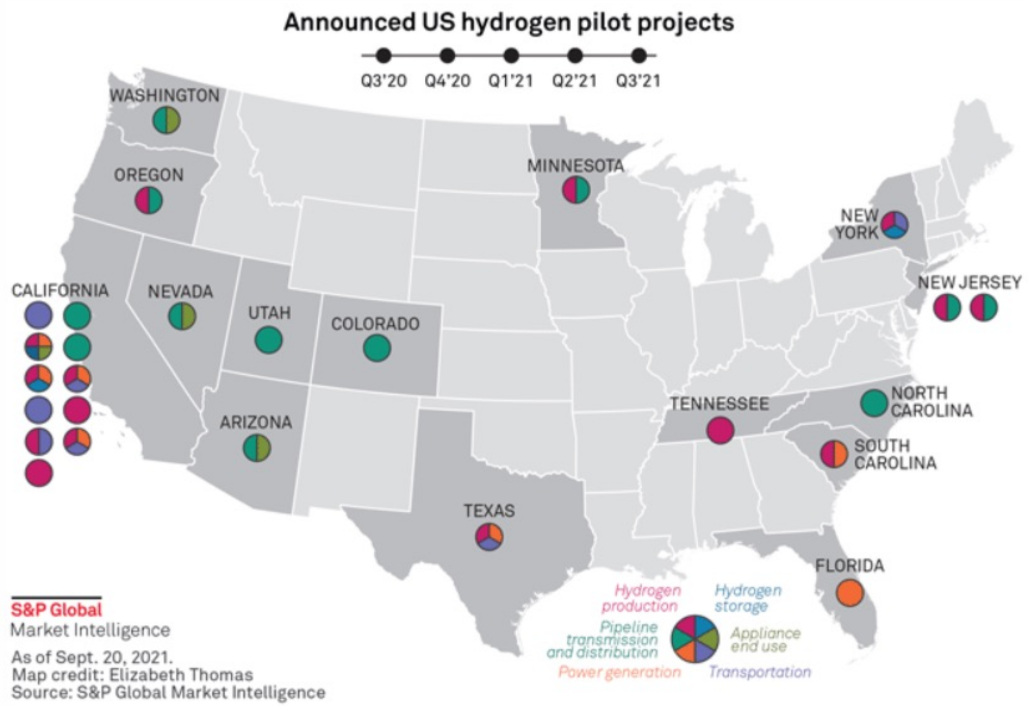
Large-Scale Demonstrations in N. America

Fossil-Free Gas: Like efficiency and renewable methane, many utilities view **delivered H_2** as essential to long-term net zero emissions goals



Source: American Gas Association (AGA), 2022. Net-Zero Emissions Opportunities for Gas Utilities, Report prepared for the AGA by ICF, link: https://www.aga.org/globalassets/research--insights/reports/aga-net-zero-emissions-opportunities-for-gas-utilities.pdf

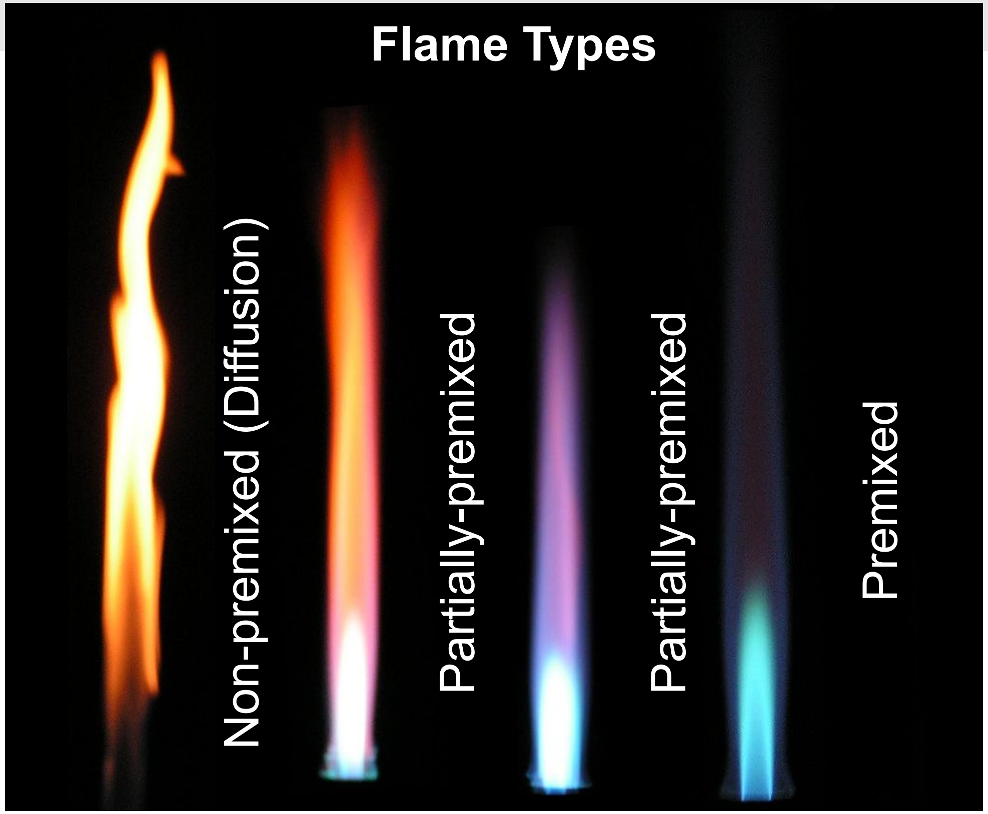
And They're Off! Numerous pilots are underway *now* (typ. ≤ 20% H_2 by vol.) with more homes and businesses in receiving H_2/natural gas over 2022.



Source: S&P Global. Add'l prominent pilots involving end users include those in Canada – British Columbia, Alberta, Ontario, and Quebec; and USA - California, Minnesota, New Jersey, New Mexico, New York, Oregon, Utah, and others.

Hydrogen Blending: Fuel Impacts

- Hydrogen has **very different** properties from natural gas
  - Lower volumetric density/smaller size (de-rating, embrittlement, etc.)
  - Greater reactivity (flammability, ignition, temperature)
  - No carbon (fewer emissions, humid exhaust, visibility)
  - Premixed vs. Partially-Premixed matters!
- For **typical, unadjusted equipment**, look for:
  - Startup issues: flashback/blowoff, ignition
  - Emissions impact: CO, NOx, etc.
  - Shift in heating: hot surfaces, de-rating, impact on efficiency



Source: Arthur Jan Fijałkowski/ WikiCommons

$\lambda = 0$ $0 < \lambda < 1$ $1 \leq \lambda$

Wobbe Index (WI) used to define fuel interchangeability

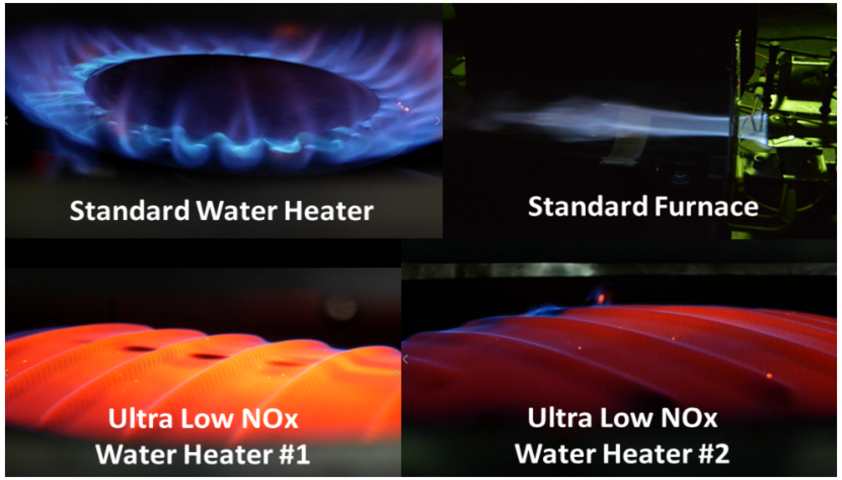
Combustion Air Requirement Index (CARI) predicts air/fuel ratio impacts

Fuel Composition and **λ** can predict S_L and $T_{adiabatic, flame}$

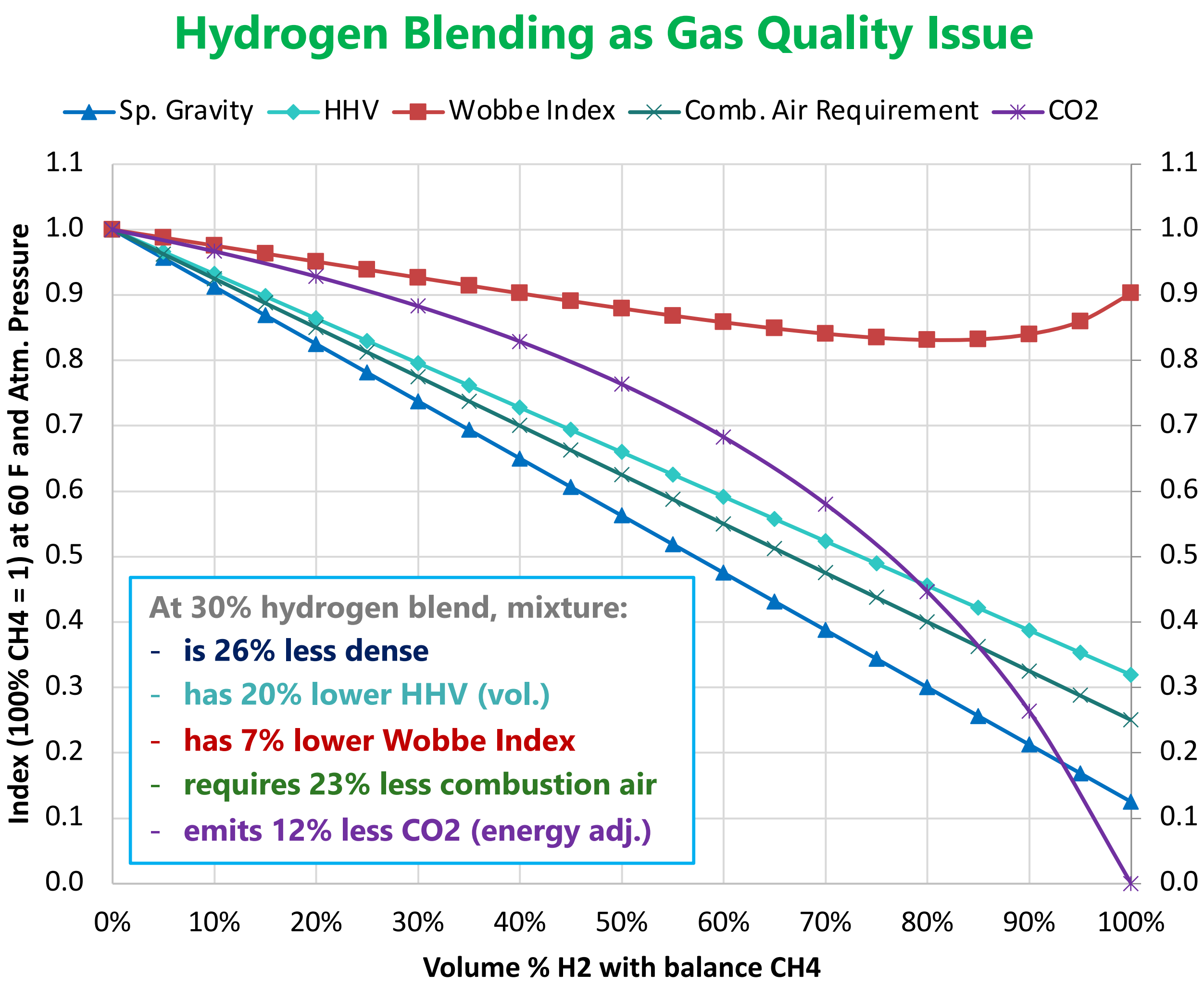
$$WI = \frac{HHV}{\sqrt{SG}} \qquad CARI = \frac{Air/Fuel\ Ratio}{\sqrt{SG_{fuel}}} \quad \text{where } \lambda_1 CARI_1 = \lambda_2\ CARI_2$$

Hydrogen Blending: Fuel Impacts

- While impacts vary, general blending levels are:
- **Low Blending:** < 10% H2 by vol.**
  - No or minor equipment adjustments
- **Med. Blending:** 10%-30% H2 by vol.**
  - Adjustments may be necessary for components/controls
- **High Blending:** > 30% H2 by vol.**
  - Specially-designed equipment required (e.g. H2 Boiler)



**Unmodified Burners with 30% H2 Blends



H2 as a Fuel – Burner Impacts

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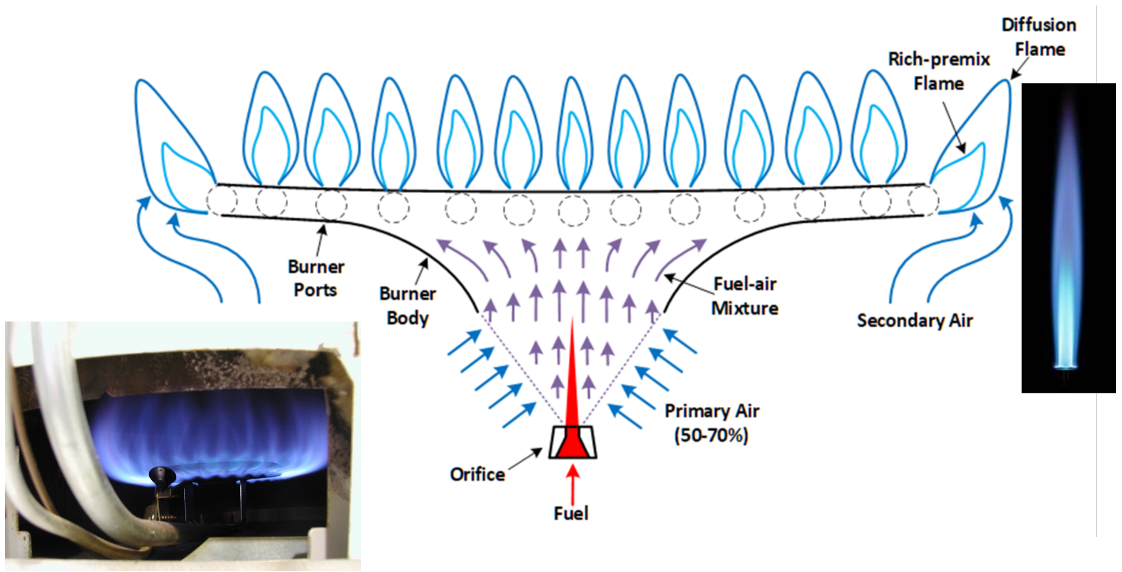
Partially-Premixed Example

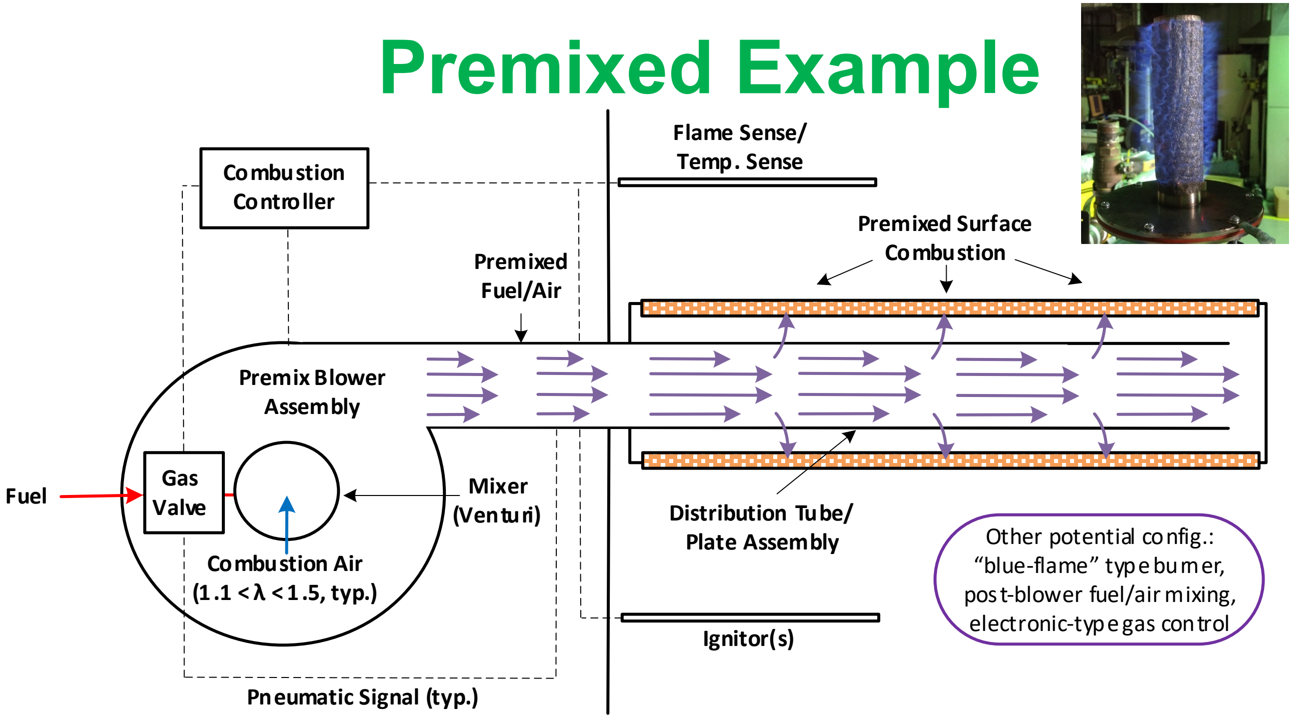


Majority of: Furnaces/RTU, storage WH, cooking, hearth, outdoor

Most of: Hot water/steam boiler, pool/process heater

Increasing H_2: Shifts $\lambda_{primary}$ to 1.0, can increase T_{flame}/S_L, but impacts are equipment specific on flame, heat transfer, air flow, NOx emissions

Premixed Example



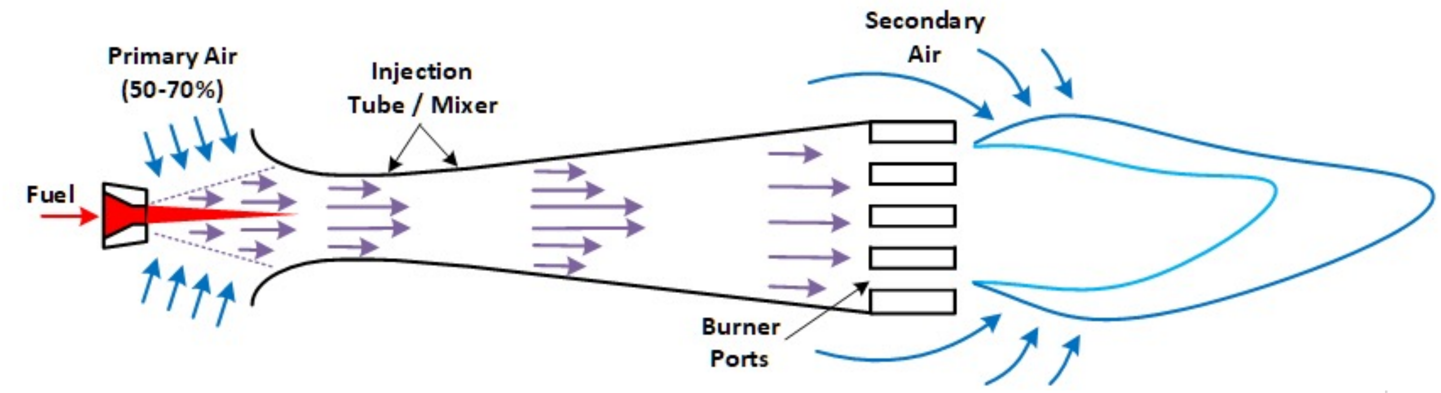
Majority of: Tankless WH, fuel-fired heat pump, boilers

Most of: Low NOx versions of PP-type equipment

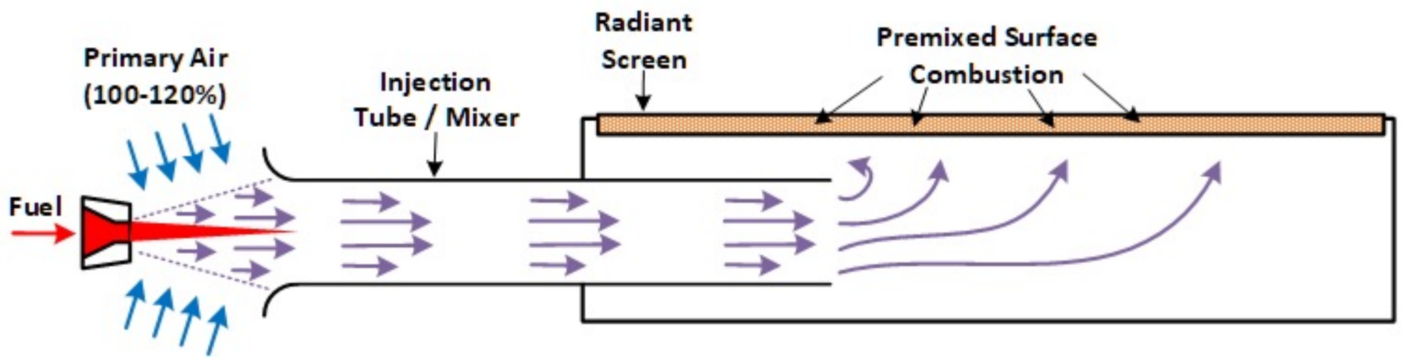
Increasing H_2: Can shift $\lambda_{overall}$ leaner for pneumatic controls, but compensating electronic controls (constant λ) result in increased T_{flame}/S_L

Atmospheric Burners Anatomy

Inshot (furnace) burner

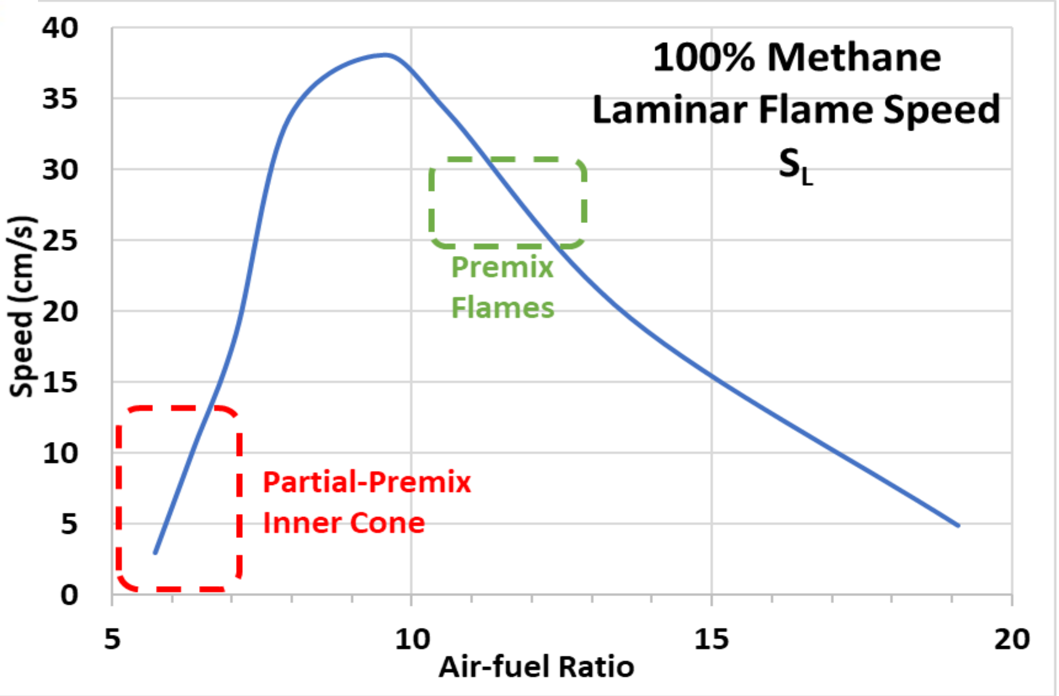


ULNOx Premixed radiant (water heater) burner



Partial-premix burners:

- Stable, compact, high-turn down
- Efficient (low CO, ~NOx)
- Cheap, reliable (100+ years in use)



Hydrogen Substitution into Methane/NG

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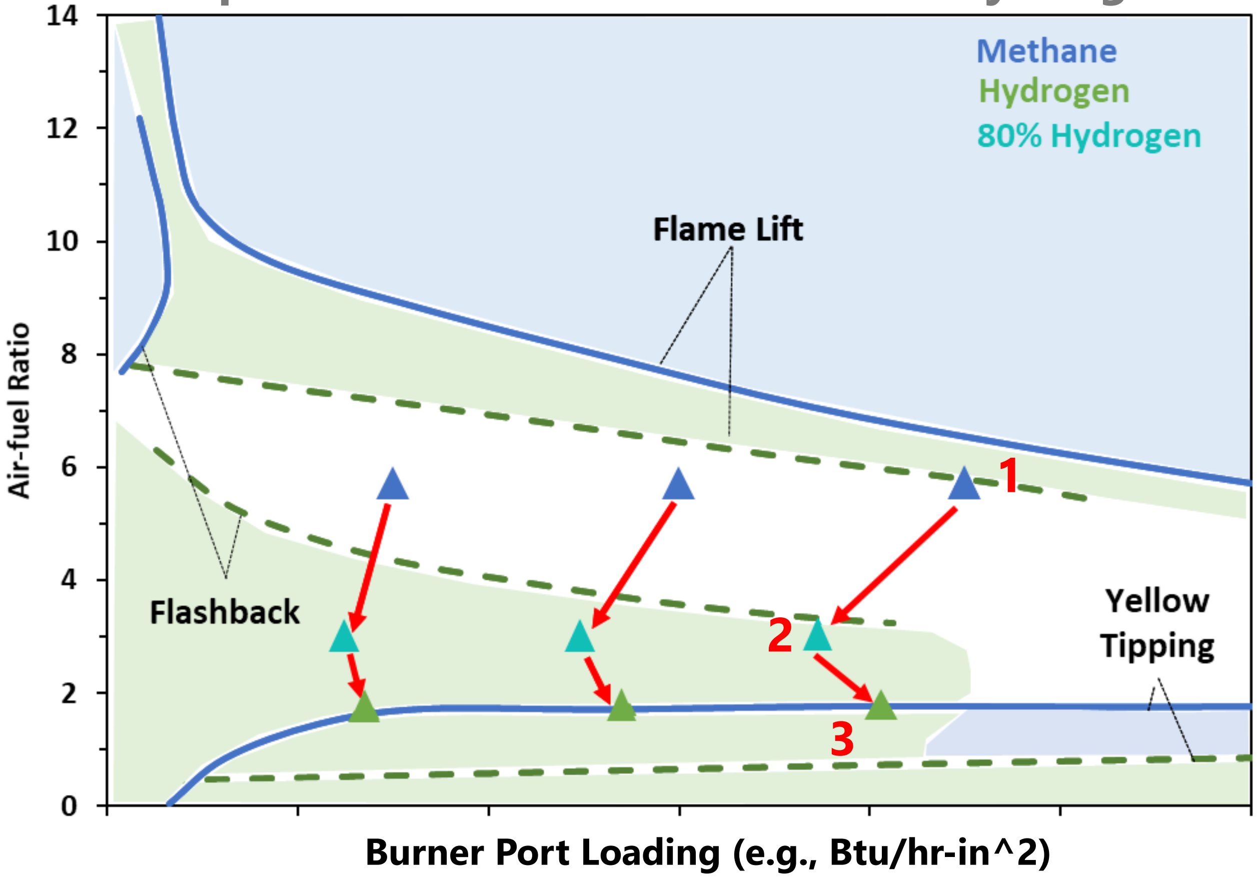
Example PP Burner Combustion Stability Diagram



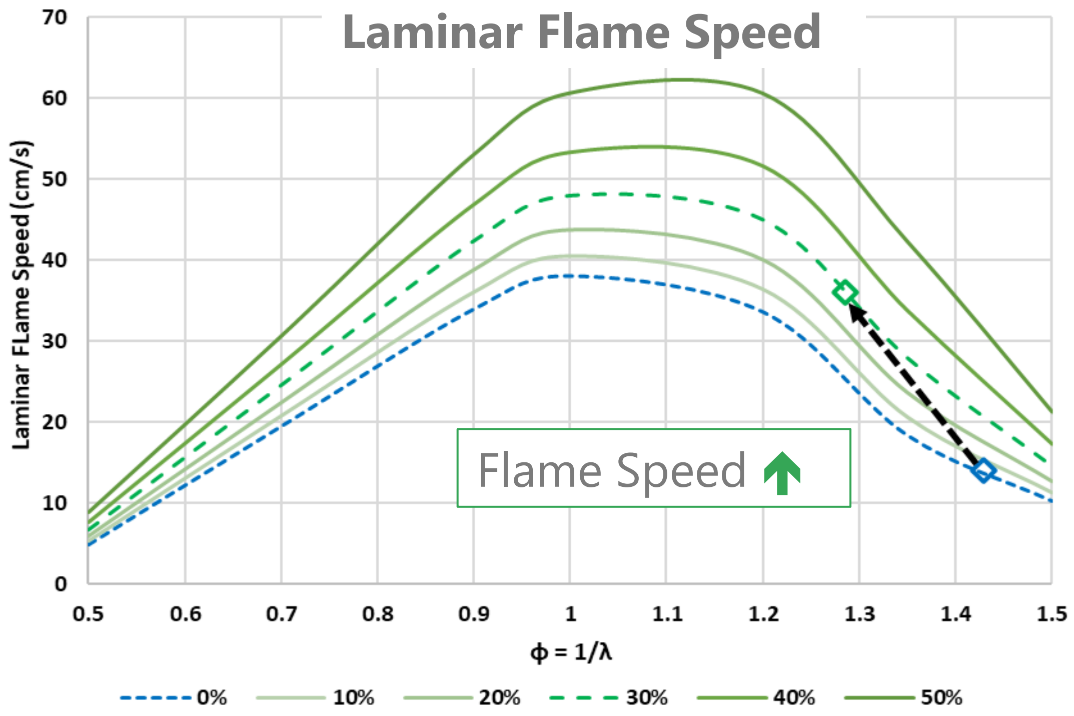
Design NG burners for Flame Lift control
Design H2 burners for Flashback control

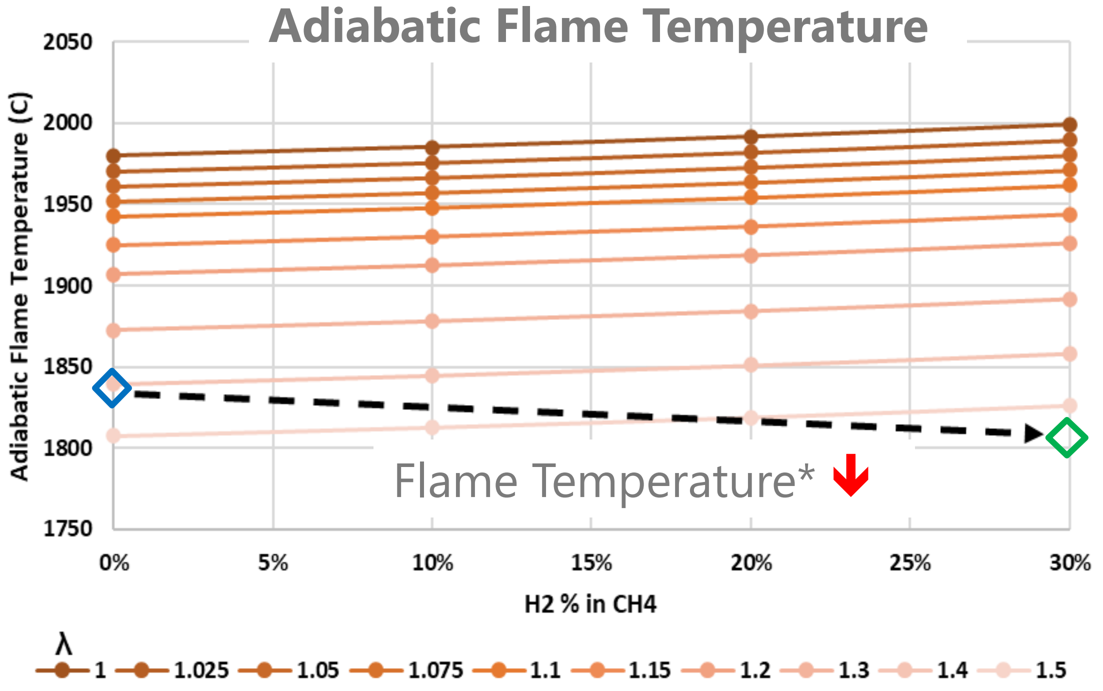
NG designed burner – H2 blending Steps:

1. **0% H2**, S_L= 3 cm/s, 60% PA
2. **80% H2**, S_L= 142 cm/s, 80% PA
3. **100% H2**, S_L= 301 cm/s, 74% PA

- Port Velocity <20 cm/s all cases
- With real burners, stability boundaries are "fuzzy"
- Burner features like flame holders, port size and spacing can modify stability regions
- Flashback more likely for low-firing rate burners (pilots, range tops, etc.)

Hydrogen Substitution into Methane/NG





Partial Premix Burner Predictions (without any changes except for H_2 substitution*)

- Firing rate ↓ (volumetric flow ↑ but energy density ↓) – 7% theoretical derate at 30% H2
- Less air is injected as H2 increases but less air is required for combustion (overall λ ↑)
- Combustion efficiency decrease* ↓ (derate and flame temperature decrease)

Overview of Efforts – Laboratory Testing

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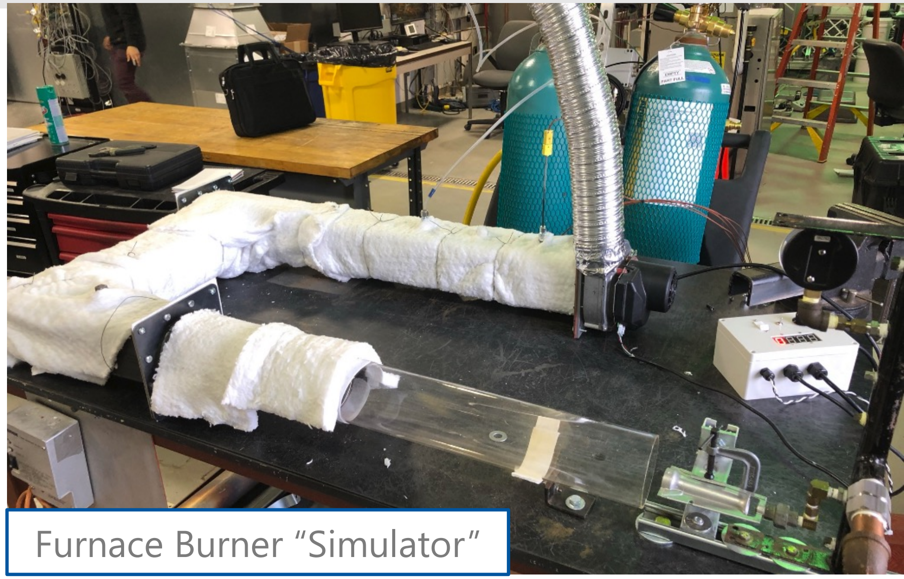
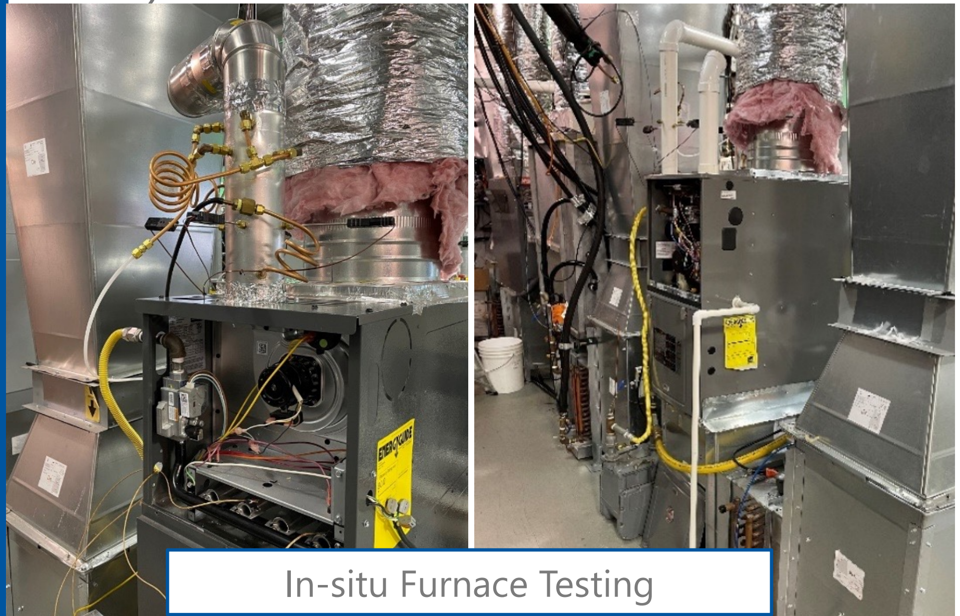
Scope of Testing - "Simulator" testing and In-situ

- Natural gas, 0%-30% H2 in CH4 in 5% increments
- Simulator tests operated manually: Furnace (in-shot), Water heater burners: Standard NOx (2), Ultra Low NOx (2)
- For in-situ, appliances with automation of loads: Two furnaces (High/Std. eff.), Three water heaters (Standard NOx, ULN #1, ULN #2)

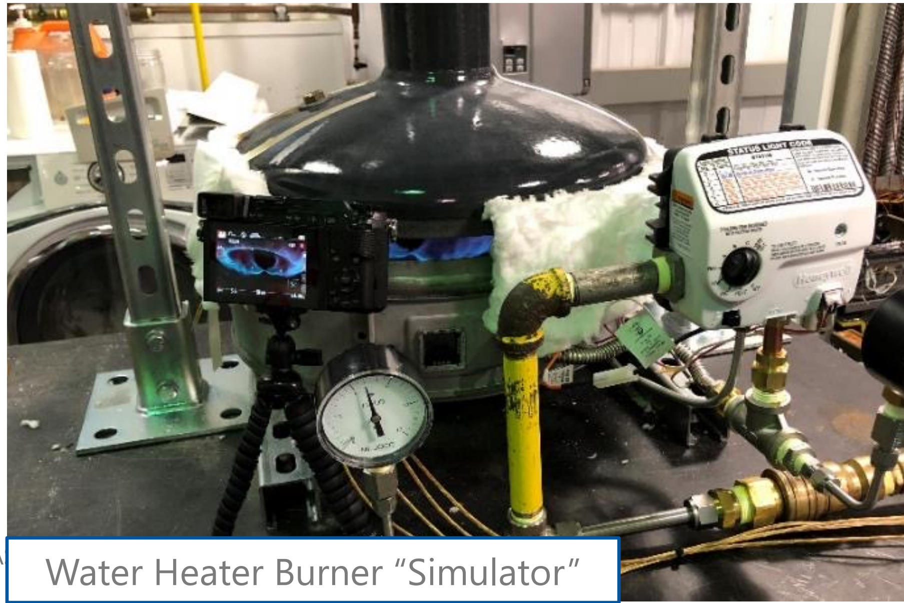


Furnace Burner "Simulator"



In-situ Furnace Testing

In-situ Water Heater Testing



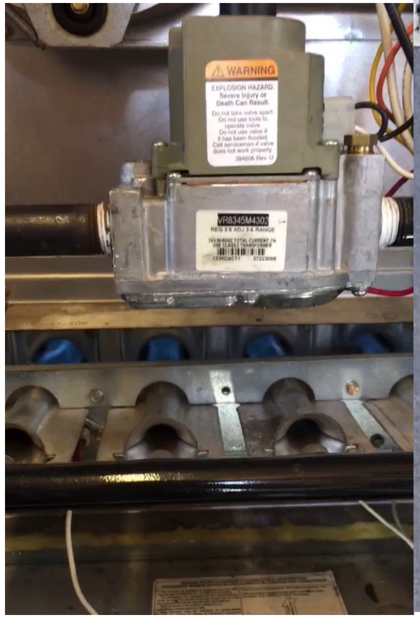
Water Heater Burner "Simulator"

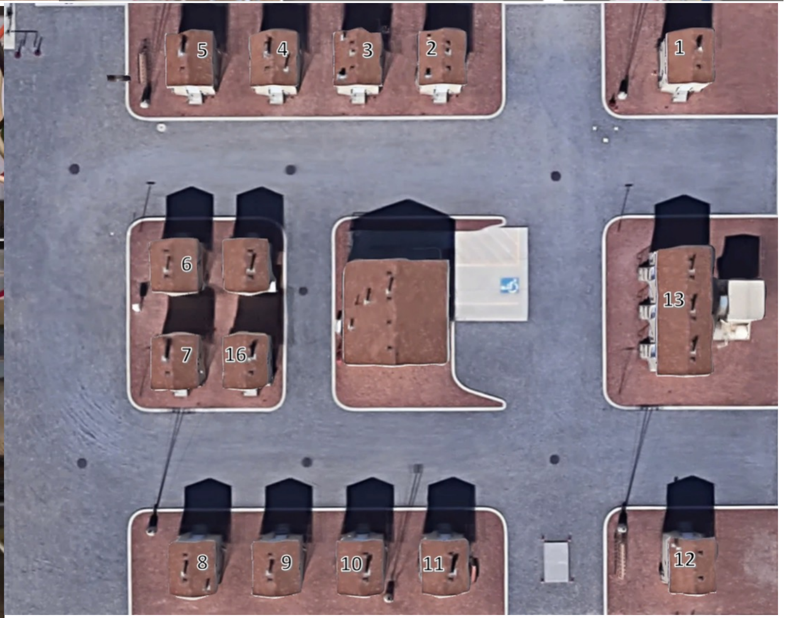
Overview of Efforts – Field Testing

- Coordinated with utility team in mid 2021, GTI sampled emissions from **15 appliances**
  - Pre/post measurement of emissions (0%-10%), material temperatures, observations on safety
  - Water heaters (standard, Ultra Low NOx), furnaces, rang es, dryers, fireplaces
- 2022 plans for three additional demonstrations, ex panding equipment population





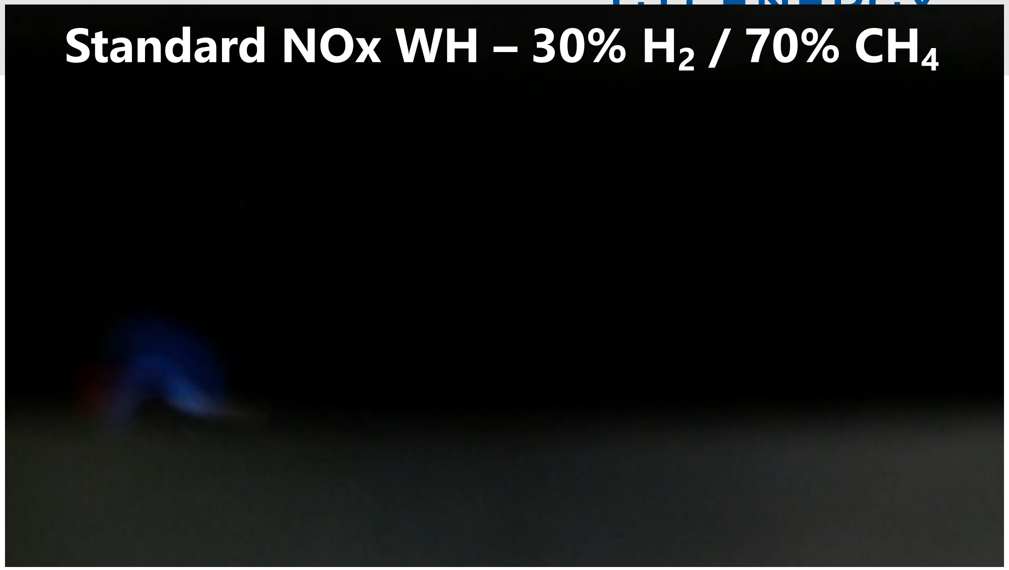


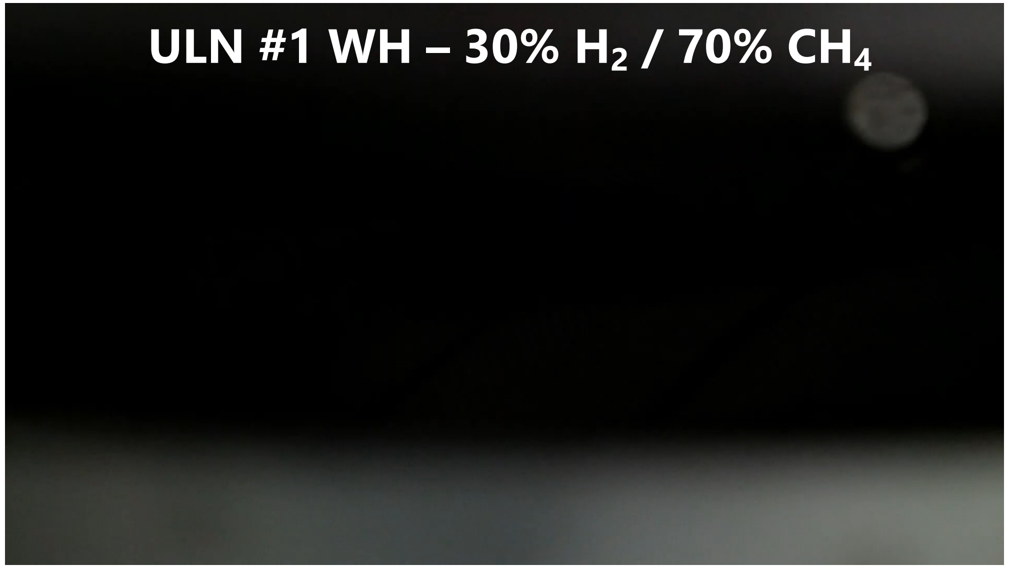
GTI sampling of residential furnace with 0% - 10% H_2 blends (left) at facility “village” (right)


Disclaimer: Conclusions based on results and methods of GTI Projects/References noted only and may not be widely applicable

Do Equipment Malfunction?

- Based on GTI Lab/Field Testing to date, **generally no** issues in normal operation
- Ignition & sustained operation successful over 0%-30% (lab), 0%-10% (field) for all equipment
- Minimal visual difference with "blue flame" burners, some dimming of radiant burners
- Limited issues seen with UCI/CSA tests (noted)





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Do Equipment Malfunction?

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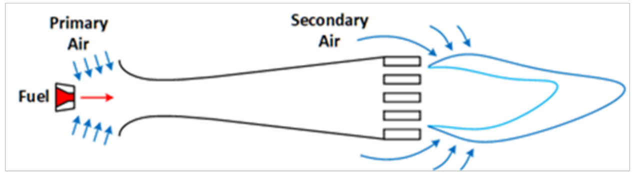
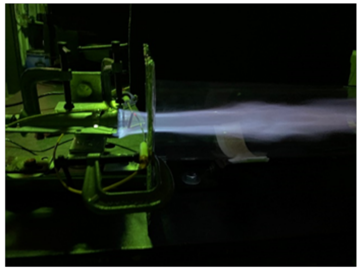
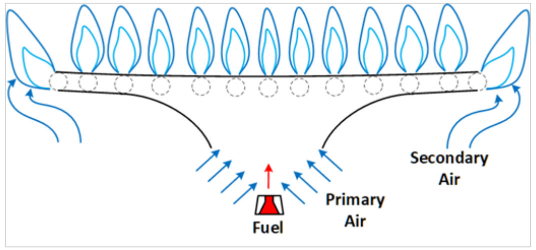
"In-Shot" Warm-air Furnace Burner (< 40 ng NOx/J)

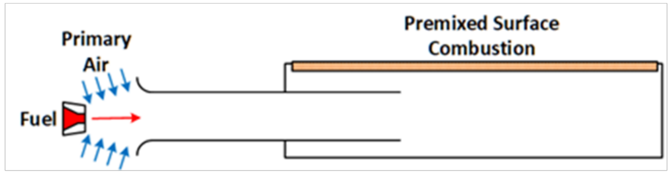


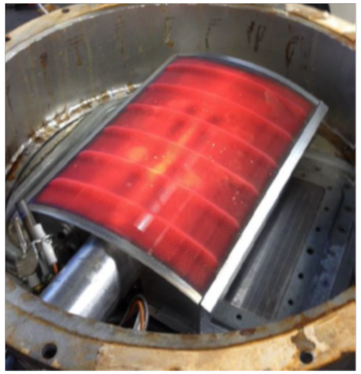


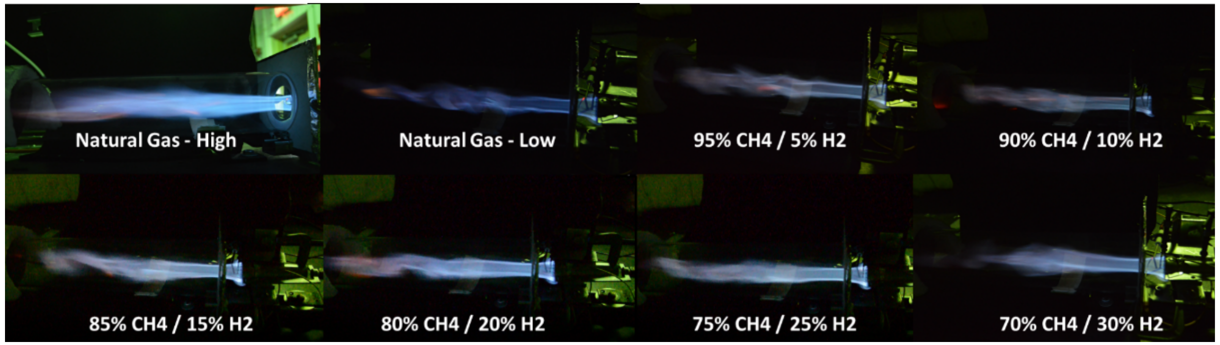
Standard NOx Water Heater Burner (< 40 ng NOx/J)

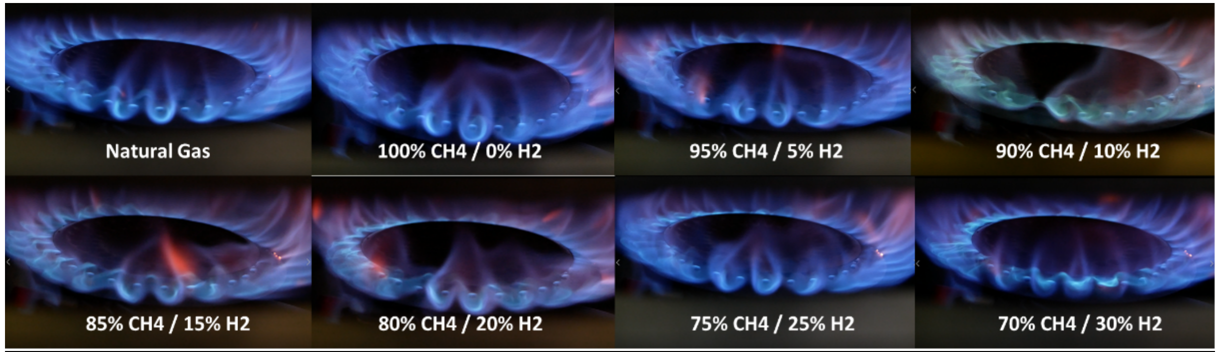


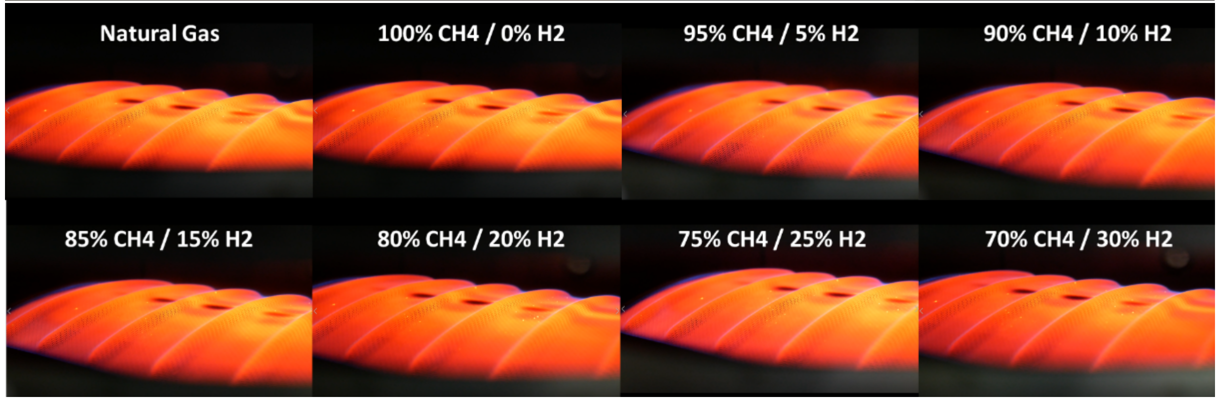
Ultra-Low NOx Water Heater Burner (< 10 ng NOx/J)











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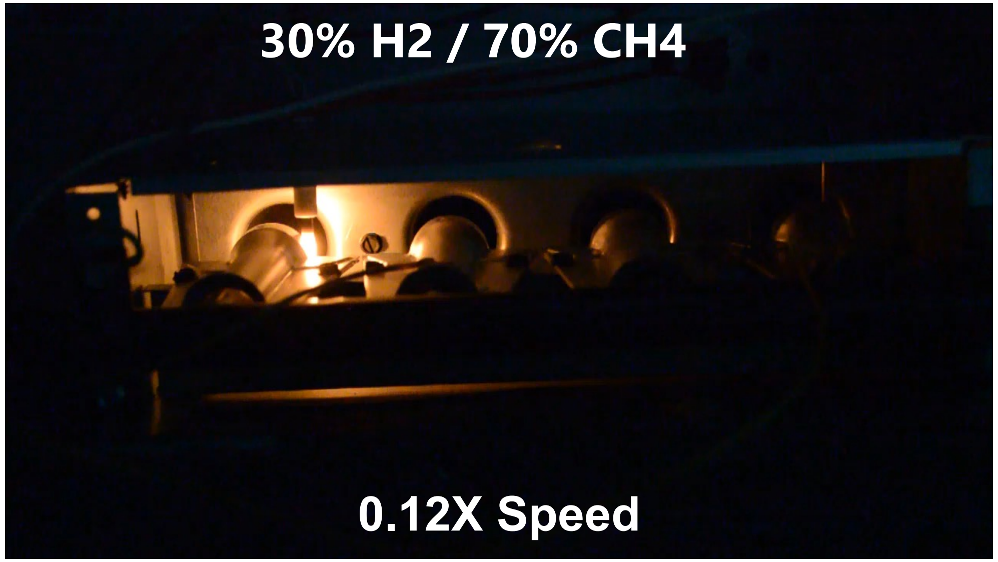
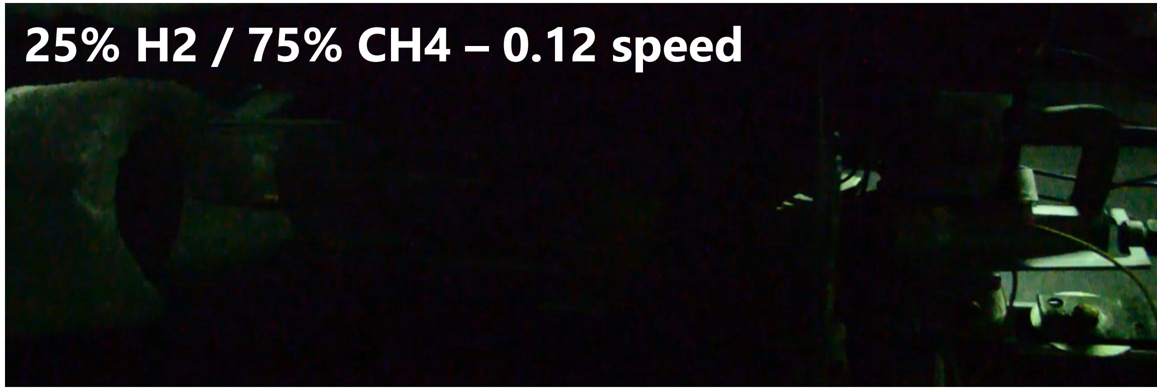
Do Equipment Malfunction?

- Measurable delay in complete “rolling” ignition for furnaces, increase with H2, cold vs. hot start, low vs. high fire
- “Flashback” created outside of furnace testing plan, **significant uncertainty why**





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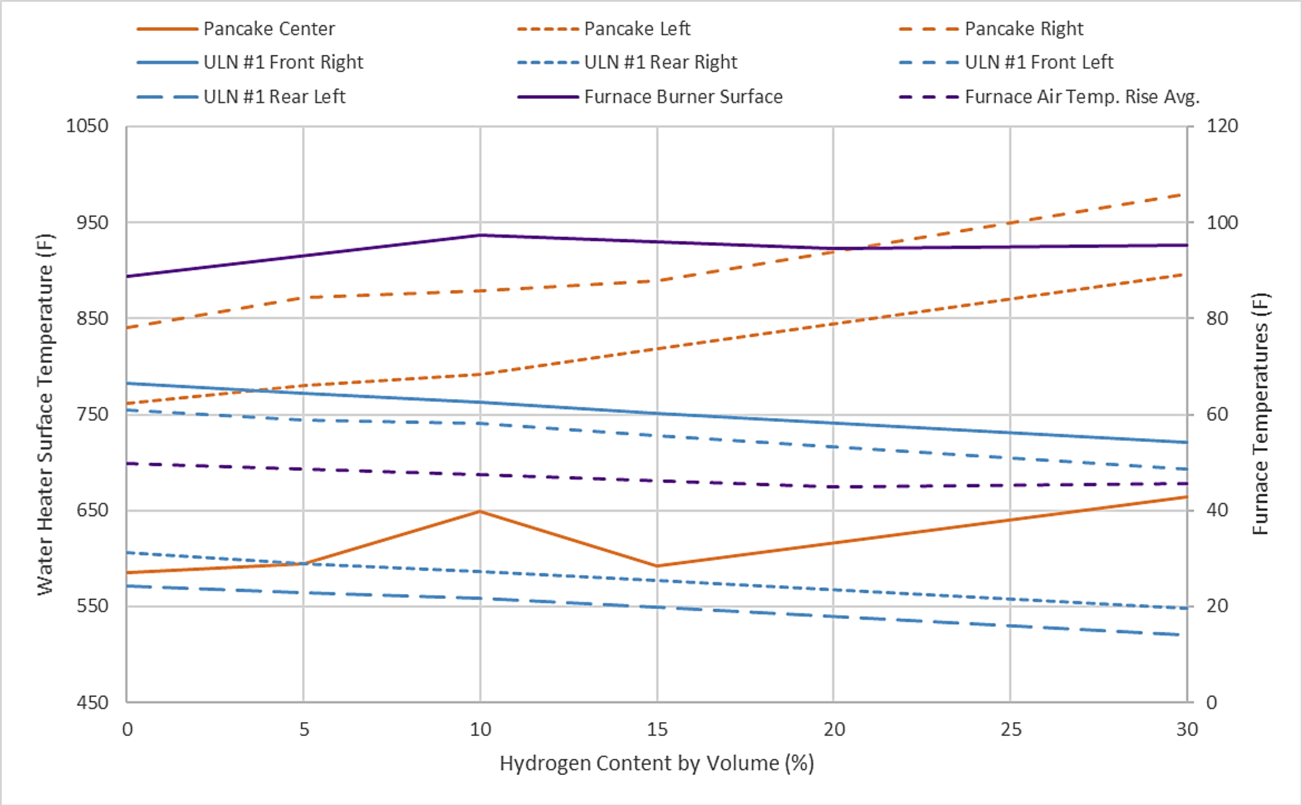
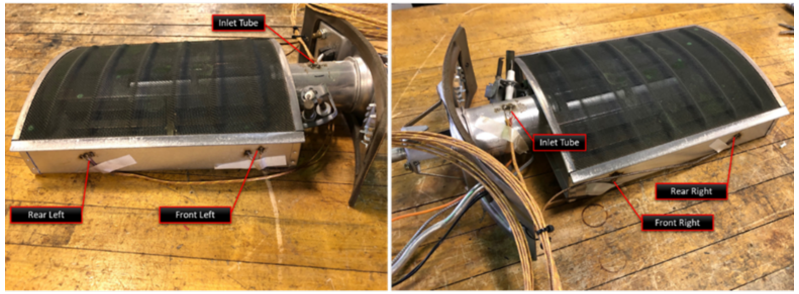
Are Temperature Increases Unsafe?

- **Likely no**, hydrogen's adiabatic flame temperature ~500°F greater than CH_4, but flame-type & dilution/de-rate impacts matter, **CSA** HX measurements agree
  – GTI measurements of burner surface temperatures in-situ / simulator

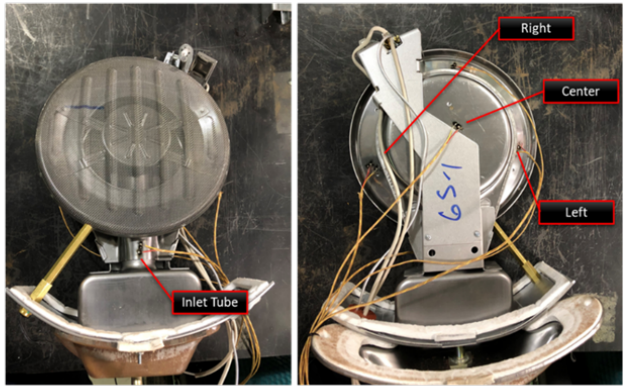
< 140 F ↑



Ultra Low NOx Burner #1



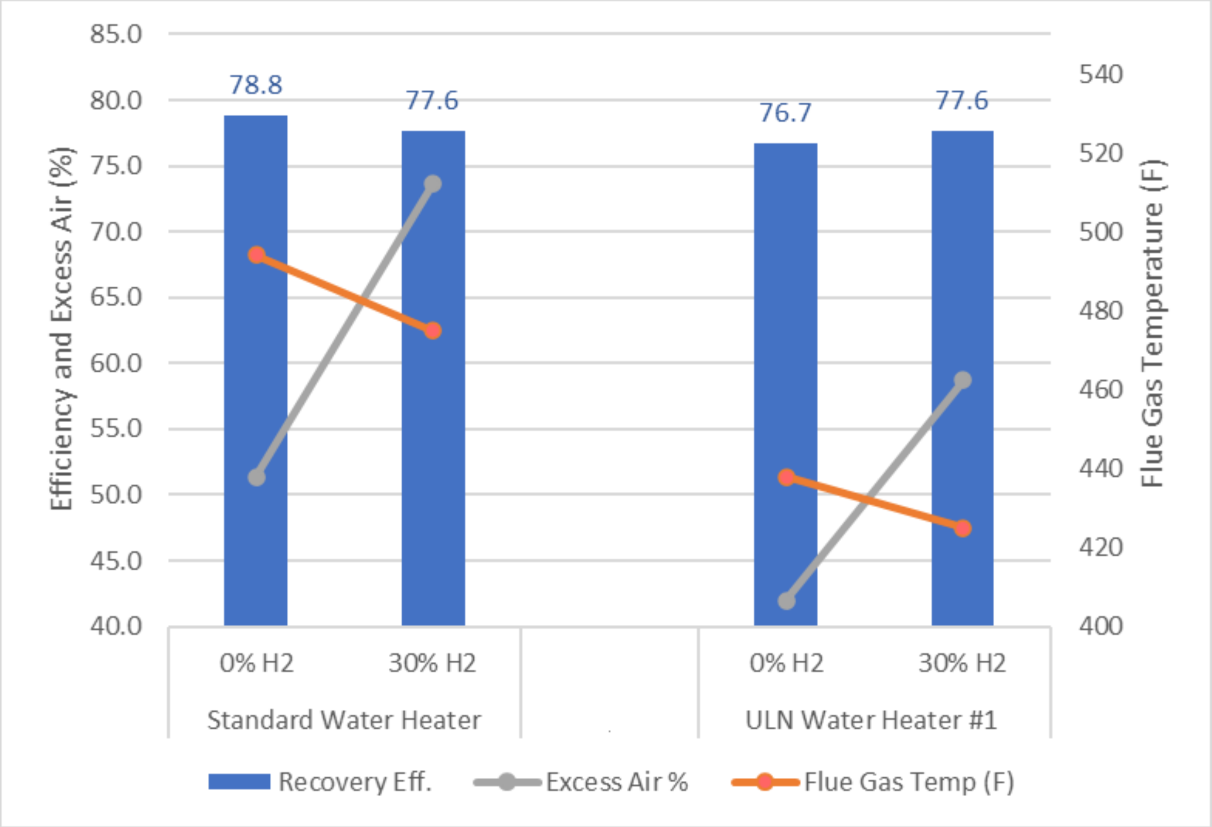
Ultra Low NOx Burner #2



Disclaimer: Conclusions based on results and methods of GTI Projects/References noted only and may not be widely applicable

Is Efficiency Impacted?

- **Possibly, but not much,** results are small and product-dependent
  - Radiant vs. blue flame combustion
  - Level of de-rate, excess aeration
  - Other factors (HX temperatures)
- GTI data show impact for water heaters
- CSA estimates of *combustion efficiency* decrease from 0% to 15% hydrogen blends
  - Furnaces 0% (no change) to 0.5%
  - Boilers 0.3% to 1.5%
  - Water Heaters 0.3% to 0.9%

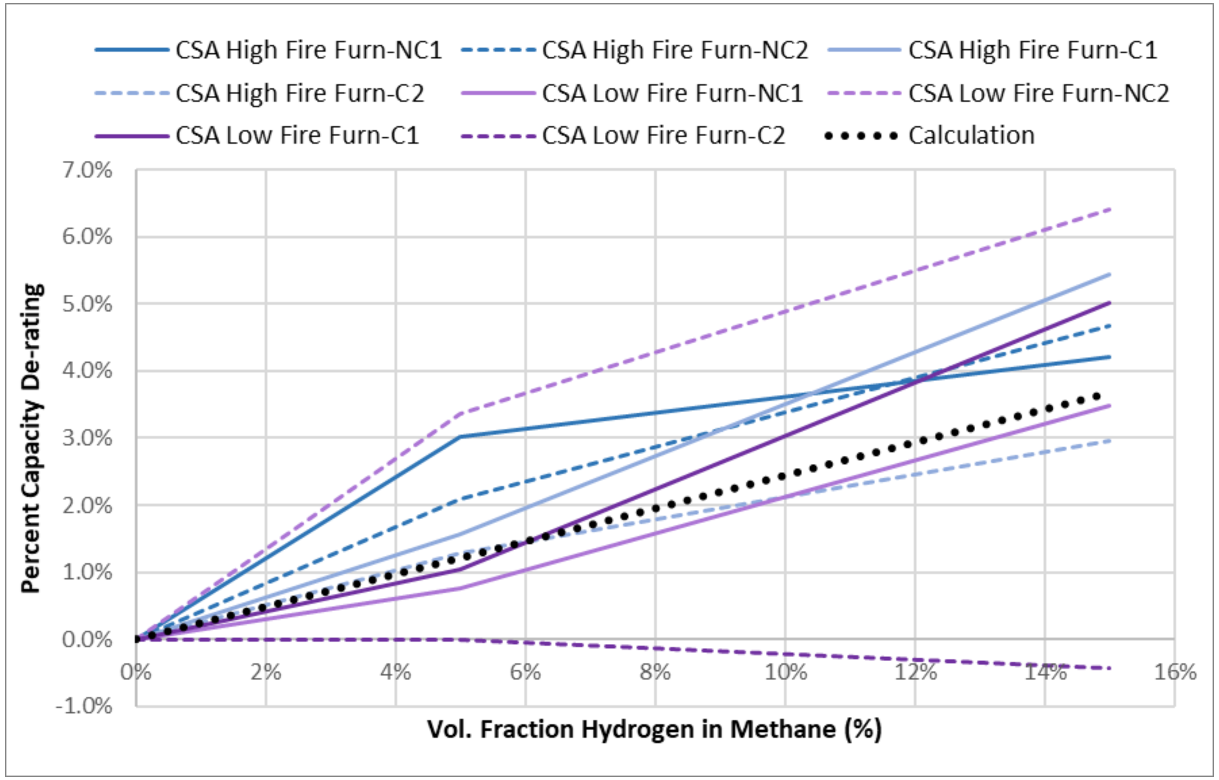


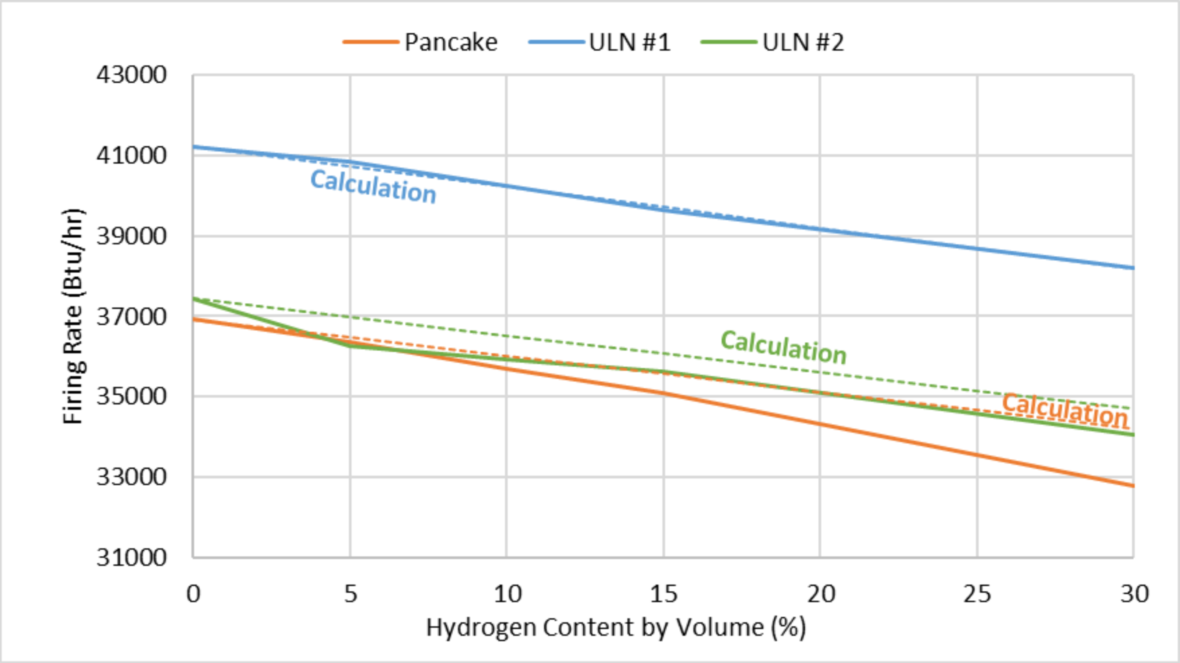
Using "recovery efficiency" DOE procedure, water heaters have *small but measurable* change in efficiency

Disclaimer: Conclusions based on results and methods of GTI Projects/References noted only and may not be widely applicable

How is Heat Output Impacted?

- **Reduced slightly in excess of Wobbe Index shift**, consistent result in literature
  – CSA data for furnaces, water heaters, and boilers, based on input





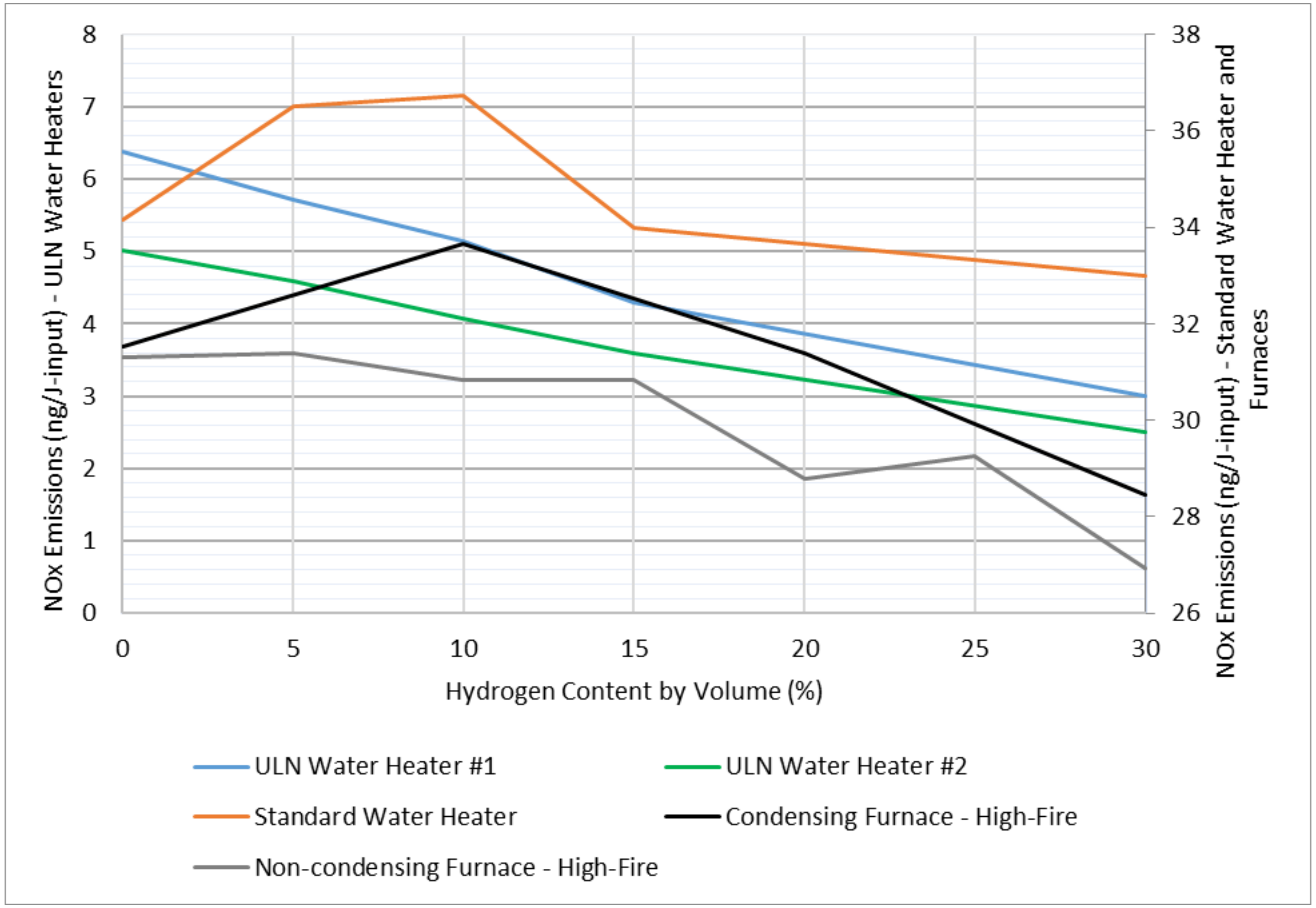
For **GTI tests** water heater input results consistent, but nuanced results – ULN #1 near exact with Wobbe Index

Data Source - CSA/AGA: https://www.csagroup.org/article/research/appliance-and-equipment-performance-with-hydrogen-enriched-natural-gases

Disclaimer: Conclusions based on results and methods of GTI Projects/References noted only and may not be widely applicable

Do NOx and CO Emissions Increase?

- **Generally no**, combustion air dilution/de-rating counter-act fundamentals for unadjusted, partially-premixed equipment
- GTI laboratory data show reduction in NOx across the board (energy input adjusted) and small change in CO emissions
- "Conventional wisdom" is NOx goes up, applies to some input-adjusted/premix-type equipment.
  - NOx formation largely, driven by T_flame, however increase is often offset by de-rate, shift in λ
  - Other emissions (UHC, CO, etc.) influenced by equipment-specific combustion context



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GTI ENERGY

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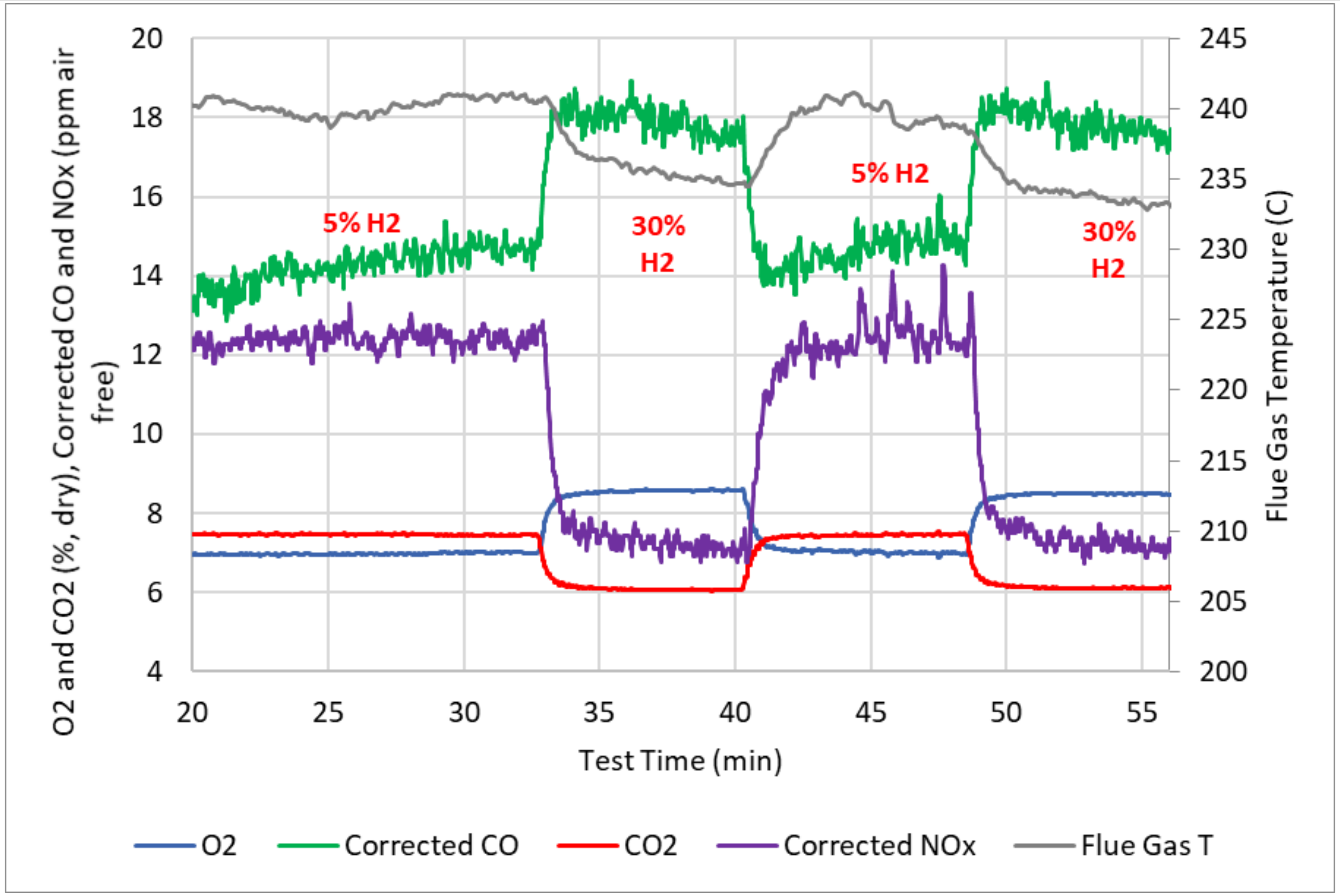


Ultra Low NOx #1 "Slug Test"

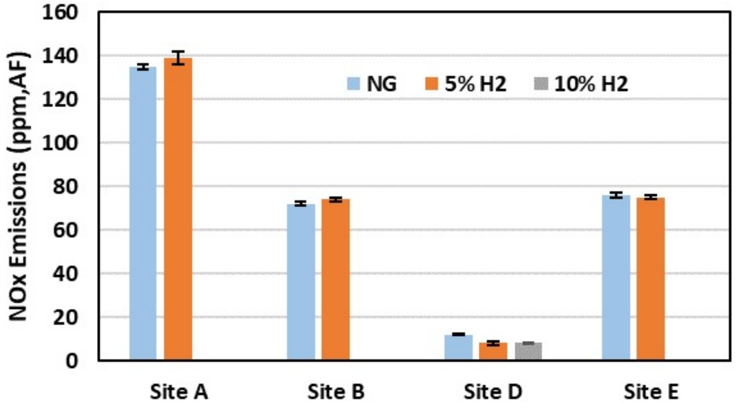
Disclaimer: Conclusions based on results and methods of GTI Projects/References noted only and may not be widely applicable

Do NOx and CO Emissions Increase?

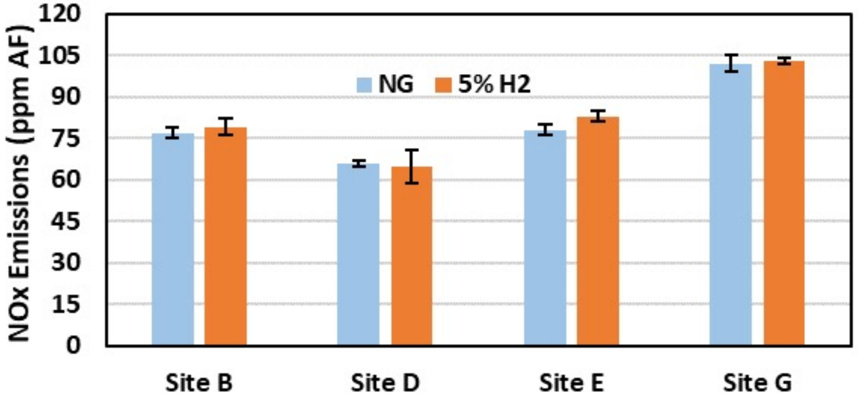
- **Generally no**, GTI field data show flat/reduction in NOx emissions (up to 10% H2, often within measurement error)

Location	Equipment Name	Burner Type
A	Water Heater #1	“Pancake” Burner
B	Water Heater #2	“Pancake” Burner
D	Water Heater #3	ULN Burner #2
E	Water Heater #4	“Pancake” Burner
D	Furnace #1	“In-shot” Burners
E	Furnace #2	“In-shot” Burners
B	Wall Furnace #1	“In-shot” Burners
G	Wall Furnace #2	“Ribbon” Burners
C	Fireplace #1	Perforated Burner
A	Range/Oven #1	Standard Range Burner
E	Range/Oven #2	Standard Range Burner
F	Range/Oven #3	Standard Range Burner

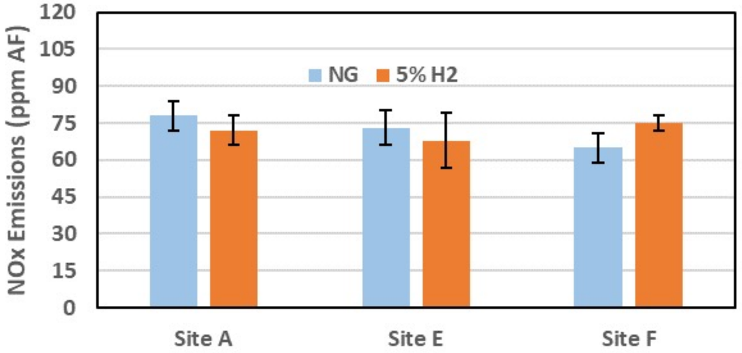
Water Heater



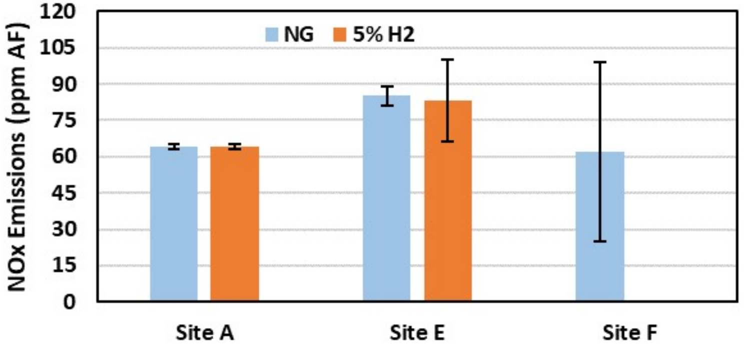
Furnace



Range



Oven



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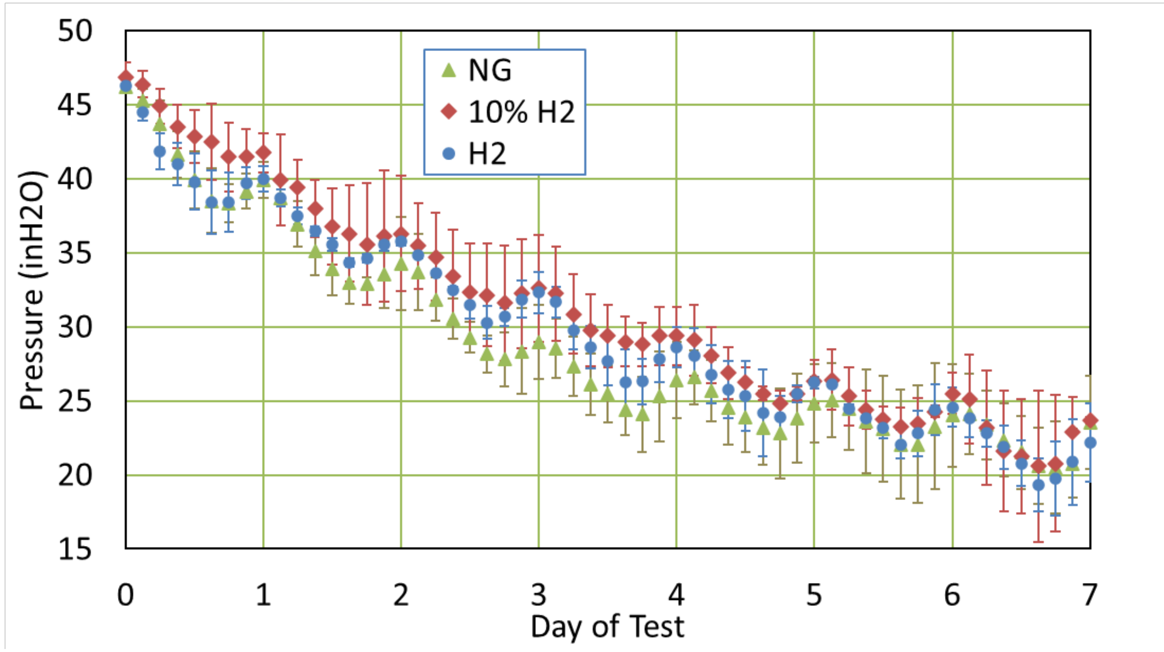
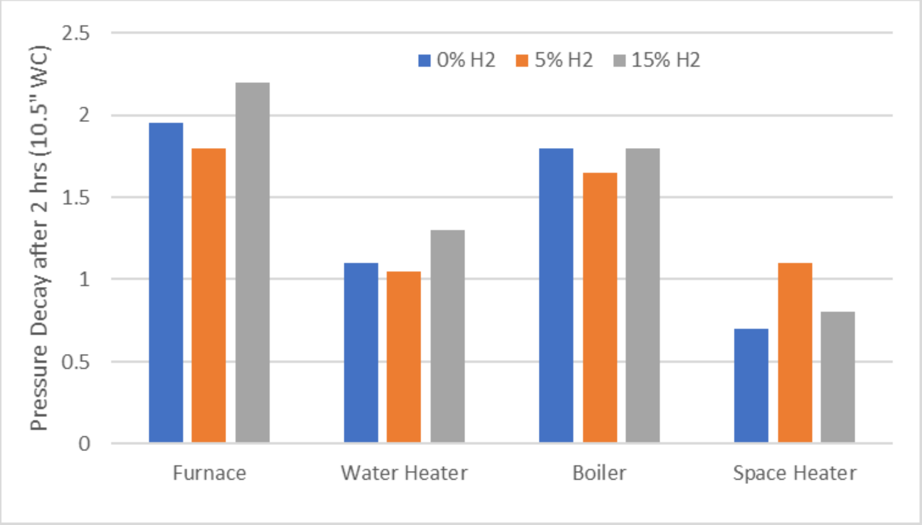
What About Indoor Leakage?

GTI ENERGY

- **Likely not worsened by hydrogen blending**, though limited data (non-GTI)
- CSA* tested equipment components & manifolds (below), not sig. difference
- Also tested pipe segments per NFPA 54 @ 5/20 psi, Steel, Copper, CSST piping/connections passed for up to 15% H2



Fun Fact: The $d_{kinetic}$ of H_2 is only ~30% smaller than CH_4, difference between baseball & softball



UC Irvine** demonstrated that natural gas, hydrogen natural gas blends, and hydrogen leak at effectively the same rate in low pressure behind-the-meter distribution

**Data Source: https://www.sciencedirect.com/science/article/abs/pii/S0360319919347275

*Data Source - CSA/AGA: https://www.csagroup.org/article/research/appliance-and-equipment-performance-with-hydrogen-enriched-natural-gases

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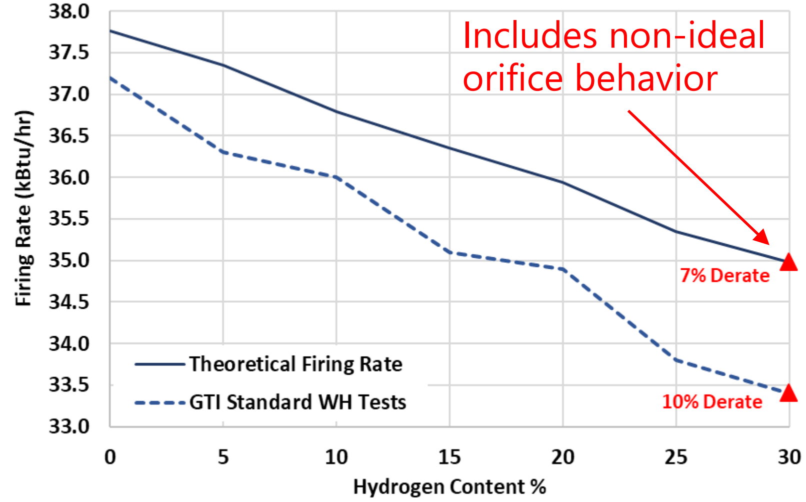
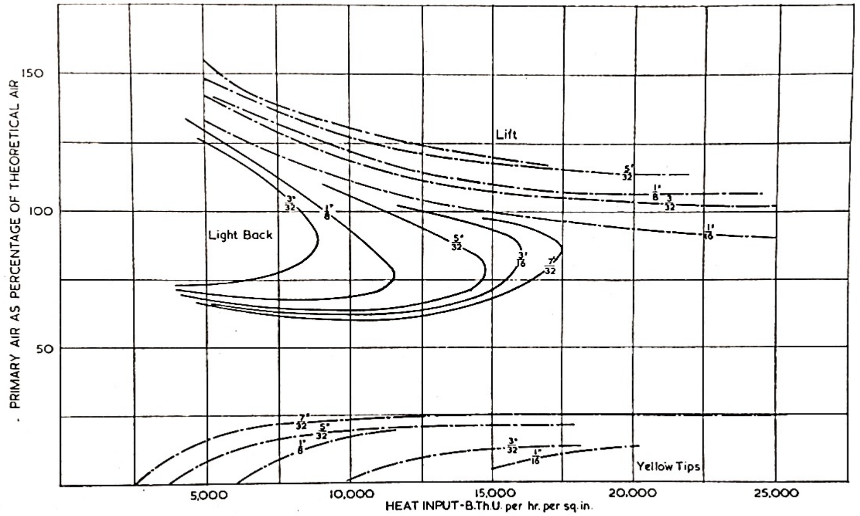
Recent Results – Recap

- Based on data collected to date in typical, unadjusted customer equipment, with blended H2/NG up to 30% by volume…
  - Cause equipment to immediately malfunction? **Not likely**
  - Lead to unsafe operating temperatures? **Not likely**
  - Adversely impact efficiency? **Not likely**
  - Significantly reduce heat output? **In excess of Wobbe**
  - Increase NOx or CO emissions? **Generally no**
  - Increase leakage within building? **Not worsened by blending**
- But what about…
  - Higher blends/pure hydrogen? Long-term impacts? Testing to failure? **…TBD**
  - Broader population of equipment (type, age, installation)? Emerging technologies and retrofit packages? **…TBD**

Higher Than Predicted Derate in Pancake Burners



Combustion Stability Diagrams for "Real" Burners



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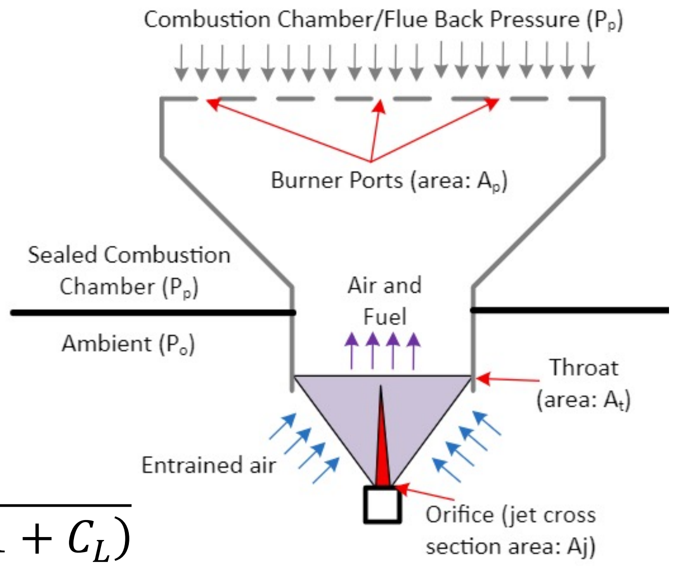
Limits of Burner H2/NG Blending

What are the limits of hydrogen blending for existing burner designs?

- "Classic" burner design texts indicate burners can be designed for operation with NG, pure H2, and blends (semi-empirical models)
- What about burners designed for NG, what will their blending limits be without?
- Can't test every burner…
- GTI Energy (SoCalGas funding) project looking at characteristics that make a burner more compatible with H2
  - Reduced order models (classic texts)
  - CFD methods development
  - Supplemental testing

Semi-empirical burner design approach (H.R.N. Jones 1989)



1. Pick a firing rate and % Primary Air

$$Q = 12.78 A_j W C_d \sqrt{P_j}$$

2. Calculate optimal throat to orifice area ratio

$$\frac{A_j}{A_t} = \frac{\sigma}{(\sigma + R)(1 + R)(1 + C_L)}$$

3. Calculate total burner port area

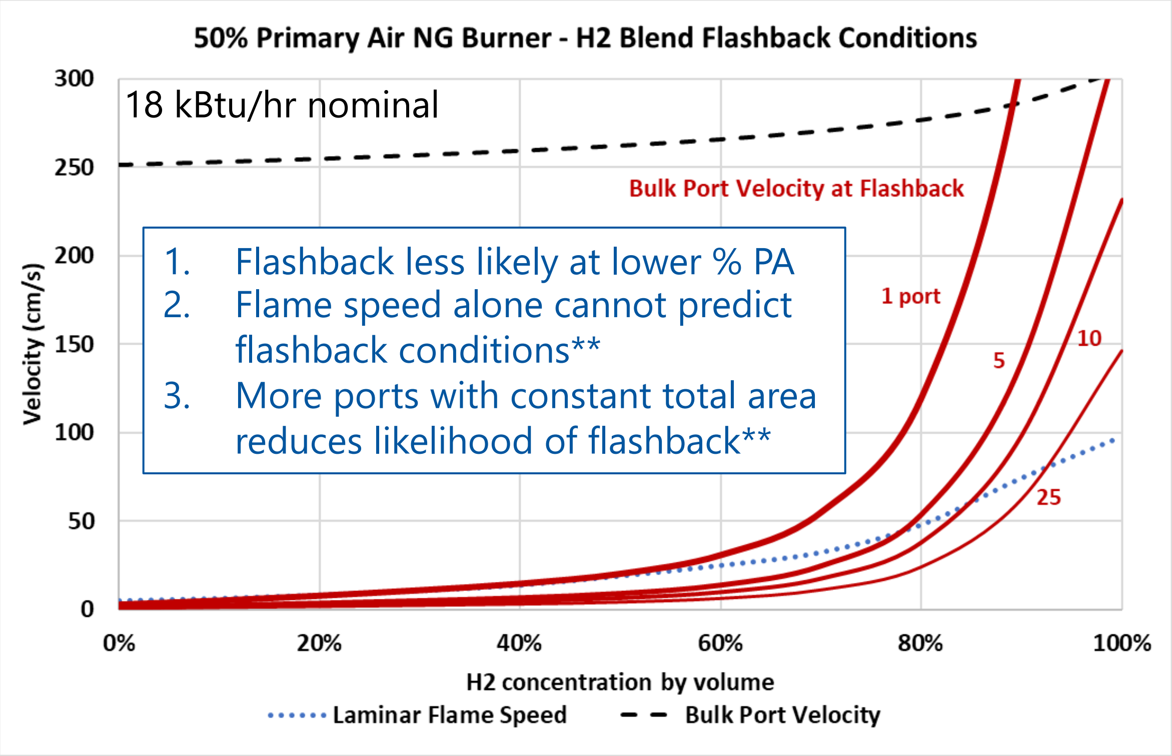
$$\frac{A_j}{A_p} = \frac{(\sigma C_{dp})}{(\sigma + R)(1 + R)\sqrt{1 + C_L}}$$

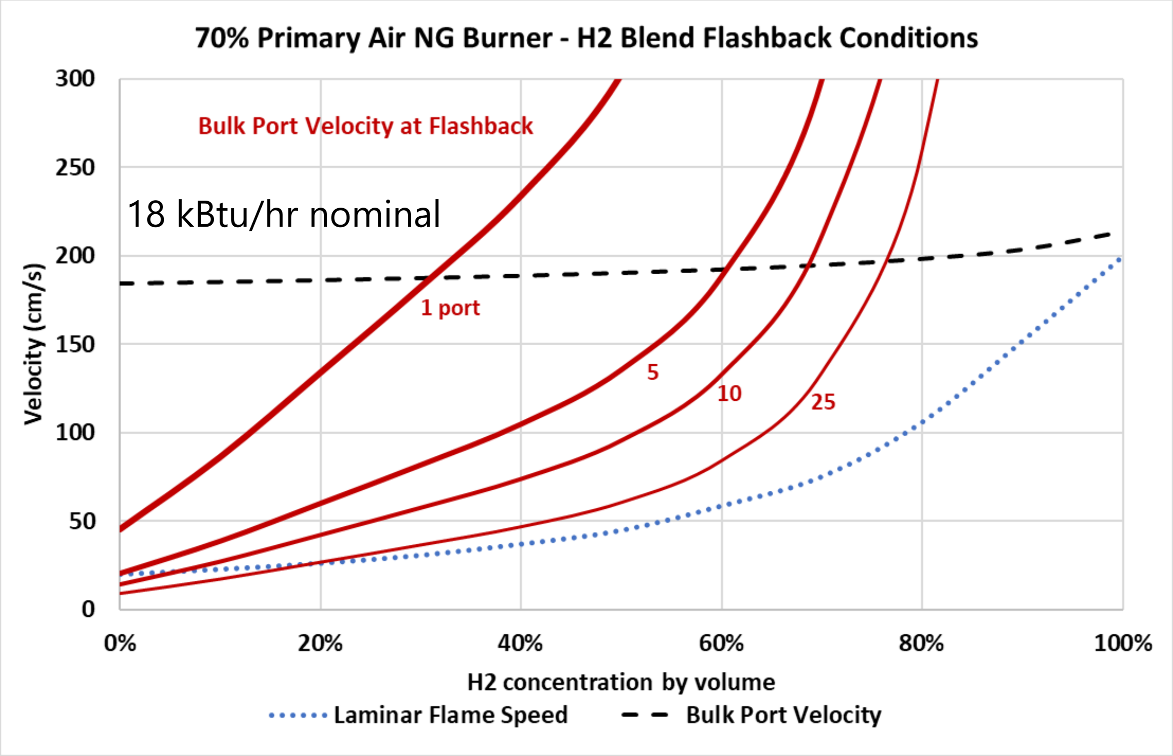
4. Design around flame lift, flashback, and yellow tipping (rules of thumb)

Limits of Burner H2/NG Blending

Predicting blending limits of NG burners (by classic means)

- Assuming NG optimally designed burner (maximize static pressure behind ports)
- For fully developed flow**, flashback occurs in the boundary layer (critical gradient theory)
- Empirical relations for critical gradient values can be used to predict** flashback conditions





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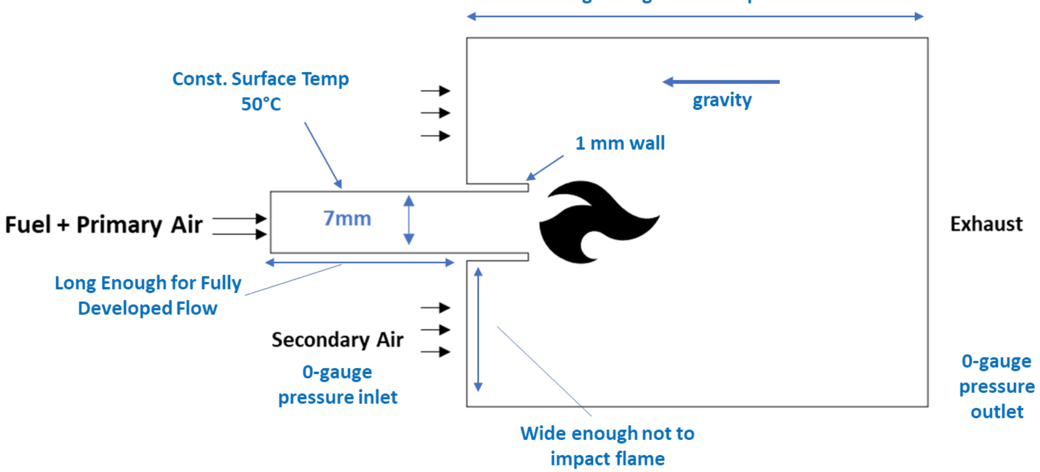
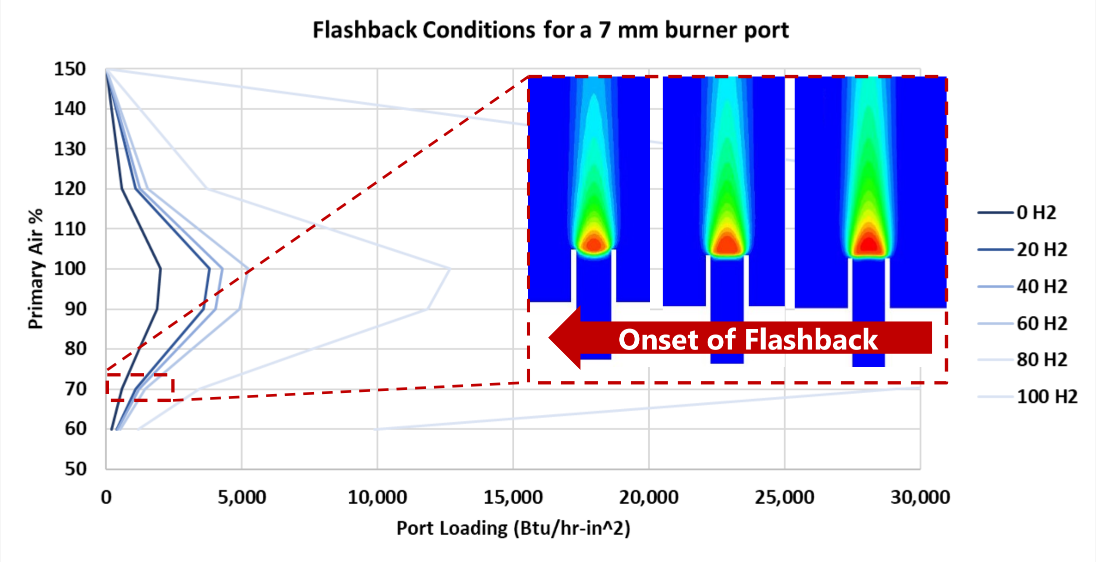
Limits of Burner H2/NG Blending

Predicting blending limits of NG burners (using CFD)

- Assessing the capabilities of different software packages and sub-models to predict flashback for H2+Methane blends
- Challenges and needs:
  - Need detailed chemistry (e.g., GRI-Mech 3.0) with good turbulence coupling
  - Good conjugate heat transfer and fine meshes
- Observations thus far:
  - "Easy" combustion models struggle
  - With above challenges met, able to predict onset of flashback (mass flow) at <16% difference compared to data
- **Real burners** (stay tuned… work in progress):
  - Flow not fully developed, transition between laminar and turbulent, and real manufacturing defects have an impact
  - Uncertain impact of flame holders and unique port designs

Research Burner to Develop Stability Diagrams





Data Source: https://doi.org/10.1016/j.pecs.2017.03.001

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Hydrogen Blending in Equip. – What's Next

- Continued testing/sampling of more diverse equipment (e.g. **heat pumps, dryers, hearths, etc.**), indoor distribution leakage, use of in-line H2 sensors
- Coordinate/support update to **codes and standards** impacted by H2-based fuels
- Development of **mitigation tech.** and high-H2 tolerant components/equipment
  - Detonation risks with increasing H2 blending
- Recent ~$3 million award to GTI-led team on H2 in **large comm. and industrial applications**
  - Test/model H2 tolerance of wide range of large equipment categories (e.g., boilers)
  - Material testing for long-term impacts, Air Quality simulation to quantify regional benefits/impacts

CALIFORNIA ENERGY COMMISSION

UCIRVINE

EPRI ELECTRIC POWER RESEARCH INSTITUTE

AHRI AIR-CONDITIONING, HEATING, & REFRIGERATION INSTITUTE

SoCalGas

PG&E Pacific Gas and Electric Company

GTI ENERGY

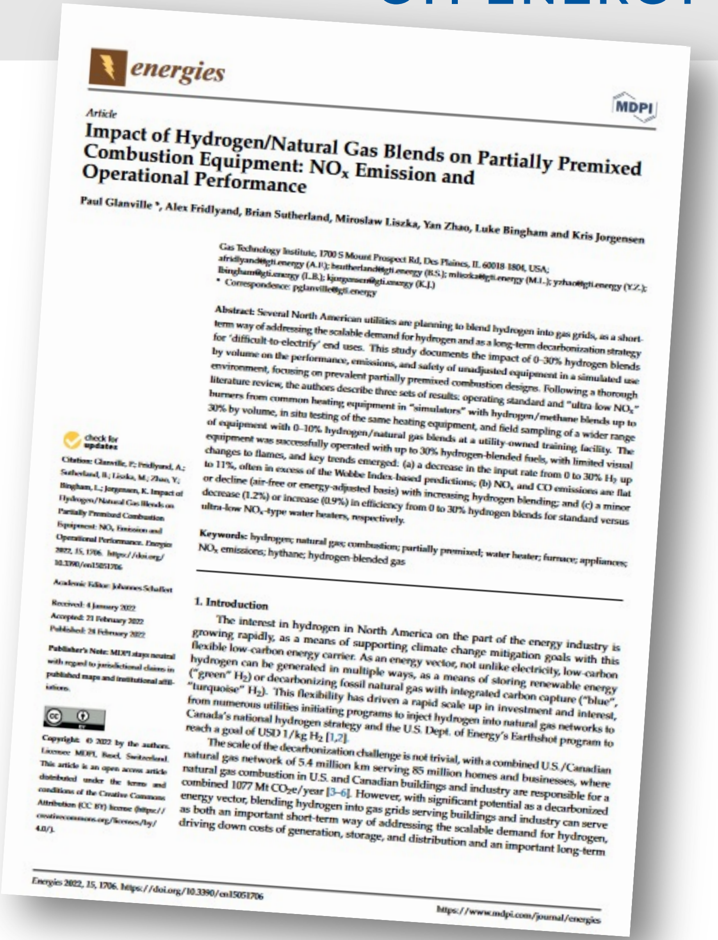
Q&A - Links and Further Reading

- GTI Energy – Hydrogen Technology Center:

  http://www.h2techcenter.energy/

- Open Access Paper - Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance

  https://www.mdpi.com/1996-1073/15/5/1706


energies

MDPI

Article

Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NO_x Emission and Operational Performance

Paul Glanville *, Alex Fridlyand, Brian Sutherland, Miroslaw Liszka, Yan Zhao, Luke Bingham and Kris Jorgensen

Research discussed supported by Utilization Technology Development (https://www.utd-co.org/)

Research team on H_2 Impacts in Buildings: Paul Glanville, Brian Sutherland, Frank Johnson, Kaushik Biswas, Kris Jorgensen, Luke Bingham, Will Asher, Yan Zhao, and others

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