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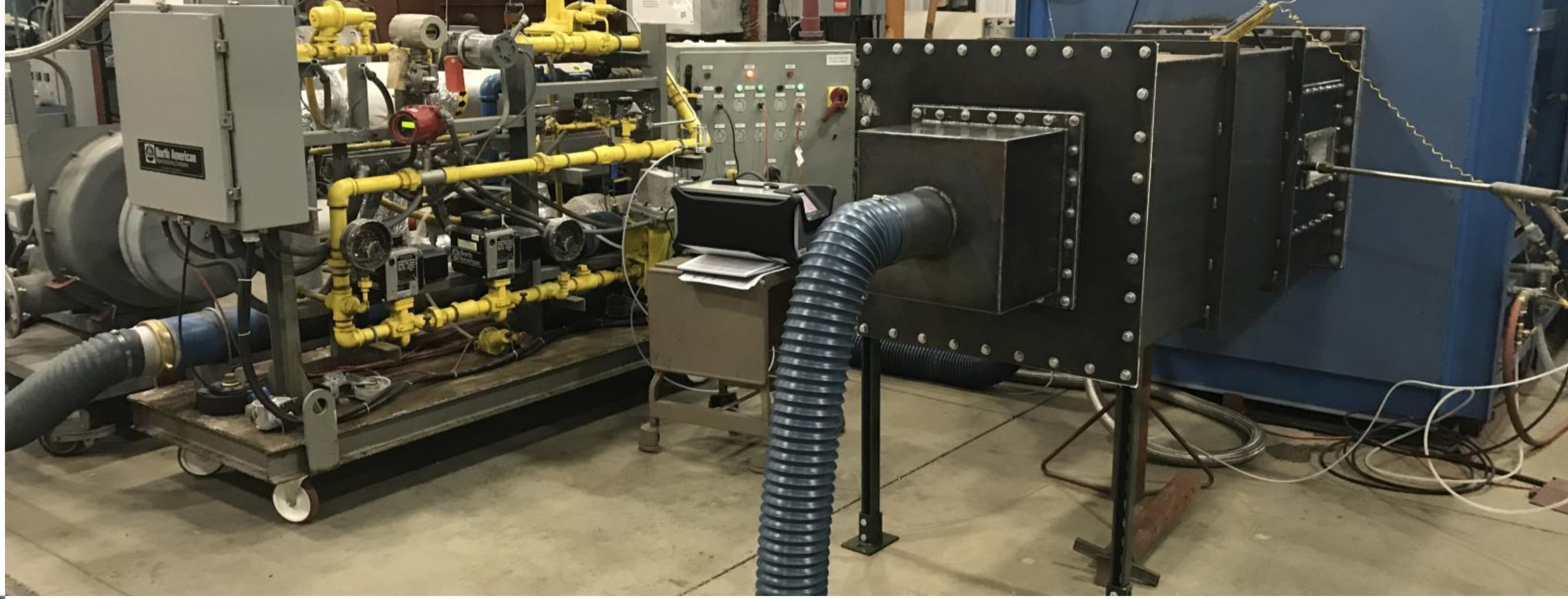

Decarbonizing Commercial and Industrial Heating with Hydrogen

Part 2 – Industrial, Boiler, Water Heater Testing; OEM Perspectives, Pulling it All Together

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Stephen Memory, **A.O. Smith**

February 11, 2025

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:

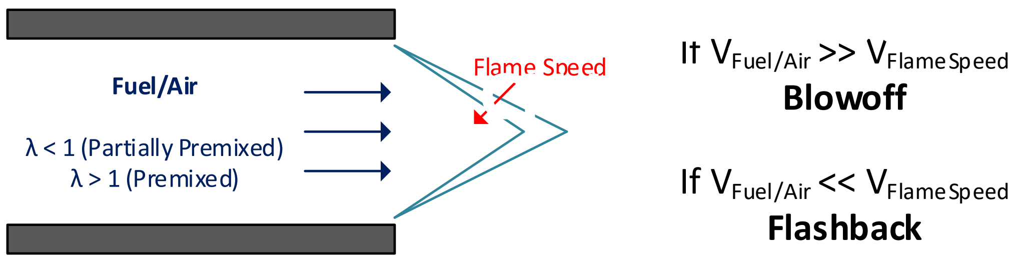
- Steam Boilers / Process Heaters
- Ovens / Dryers / Kilns
- Heat Treating / Furnaces

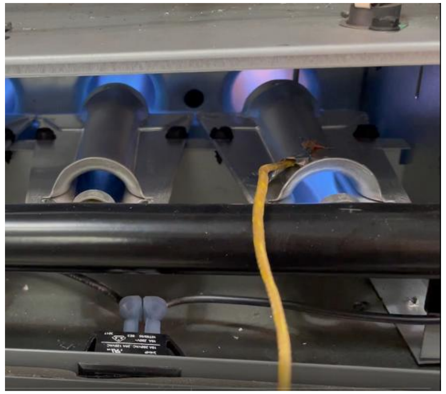
Project Motivation – PIR-22-001

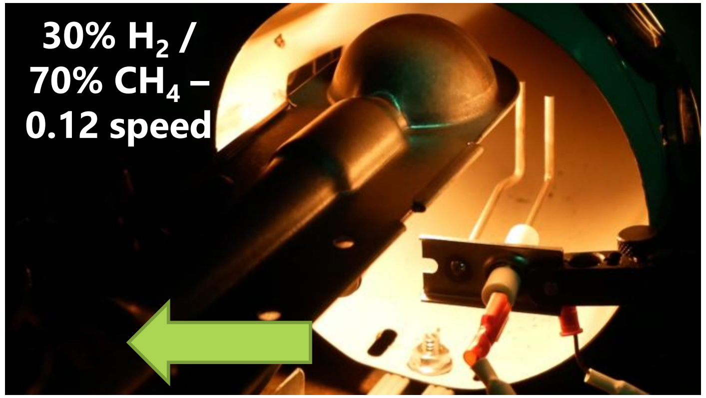
What do we typically look for with H_2?

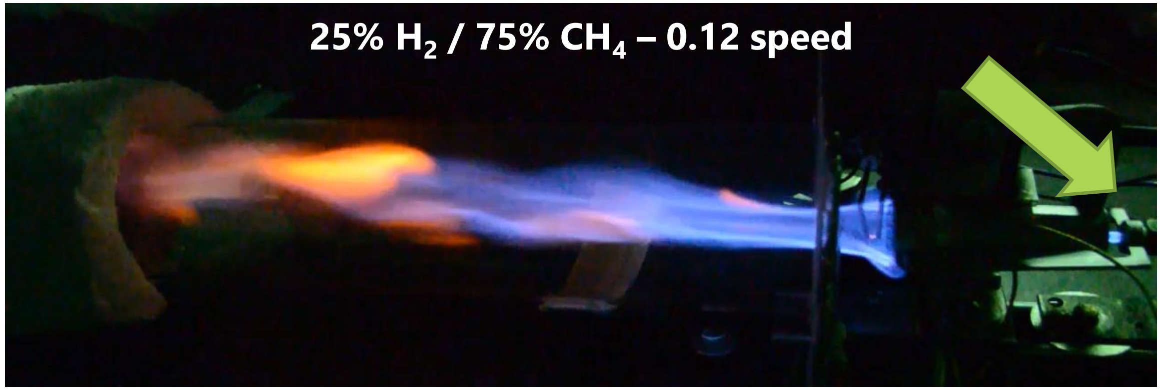
- Short-duration testing looks at…
  - Flame stability/safe ignition/flashback
  - Surface temperatures/Radiant Output
  - Capacity/Efficiency/Modulation
  - Emissions (NO_x, CO, CH_4, or H_2)
  - Impact of variable blending/balance fuel
  - Static leakage enhancement
- But what about…
  - Higher blends/pure 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





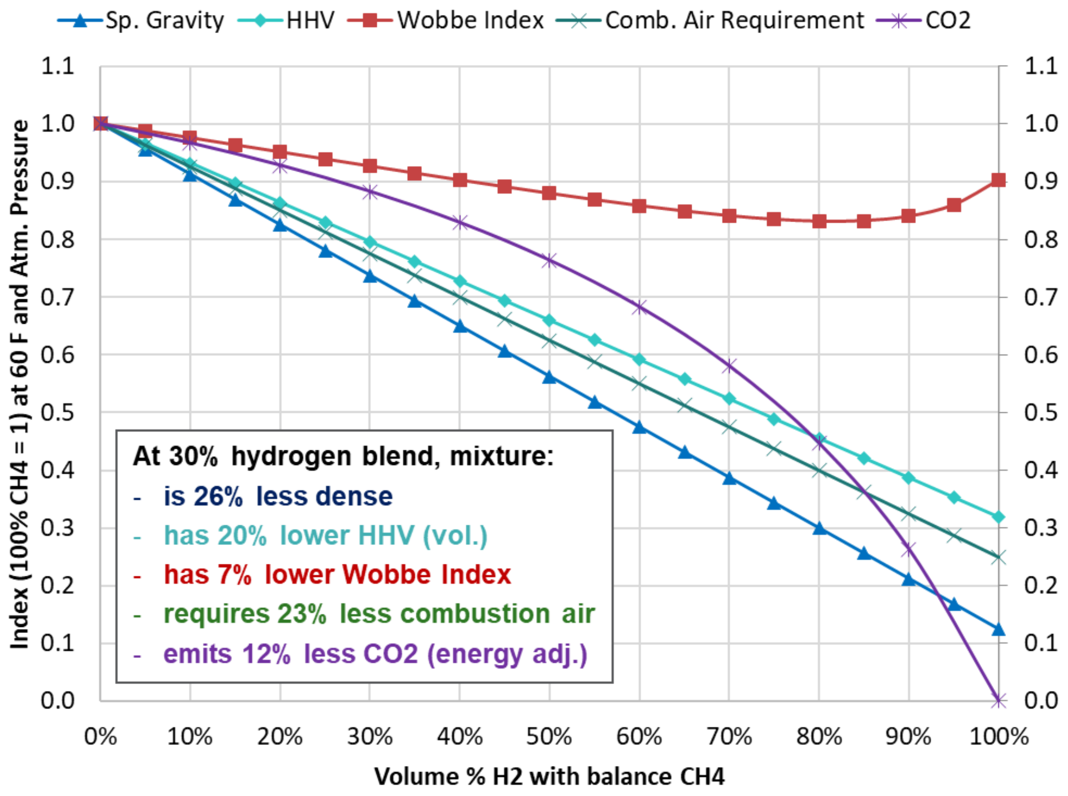




* For review of H2/NG impacts on combustion equip., see GTI paper: https://www.mdpi.com/1996-1073/15/5/1706

Hydrogen – Challenges and Opportunities

- Hydrogen has **very different** properties from natural gas
  - Lower vol. density/smaller size (de-rating, embrittlement, etc.)
  - Greater reactivity (flammability, ignition, temperature)
  - No carbon (fewer emissions, humid exhaust, visibility)
  - Impacts on flame detection, ignition controls
- Blending with natural gas, **interchangeability is complex**
  - Gas quality commonly defined by inter/intrastate pipelines, regulating HHV, major/trace constituents
  - *Some* utilities and operators specify Wobbe Index limit (R/LNG)
  - **Example**: If 950 Btu/SCF is HHV limit, low CH_4 mix (90%) permits up to 17% H_2 while high CH_4 mix (96%) permits up to 6% H_2



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 $T_{adiabatic,\ flame}$

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

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	Up to 50 MMBtu/h input	300 to 3,000 kBtu/h input
	Hydronic/Hot Water		
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)

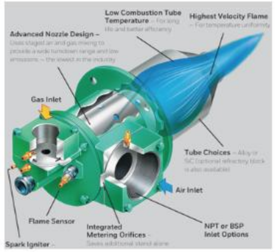
- Manufacturer perspective on H_2 applied to heating equipment and testing results

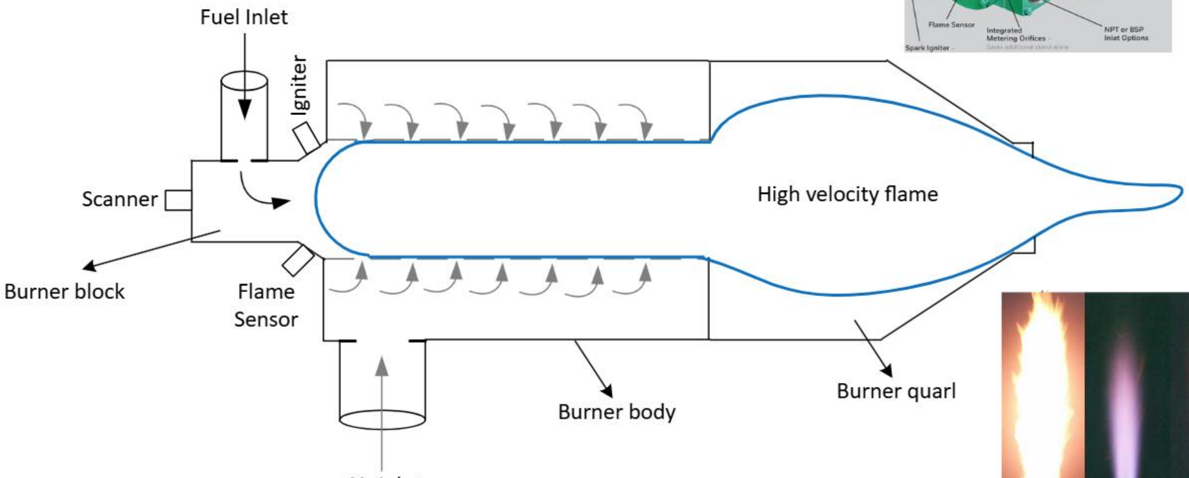
Pulling it All Together – H_2 Big Picture (GTI)

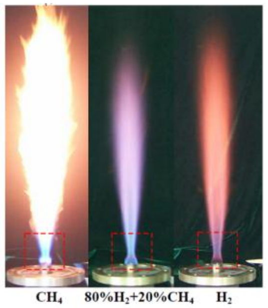
- Putting research data into broader context, including techno-economics, codes & standards, trends in test data, and H_2 safety

Overview of H_2 Basics – Industrial Burners

Non-Premixed Example



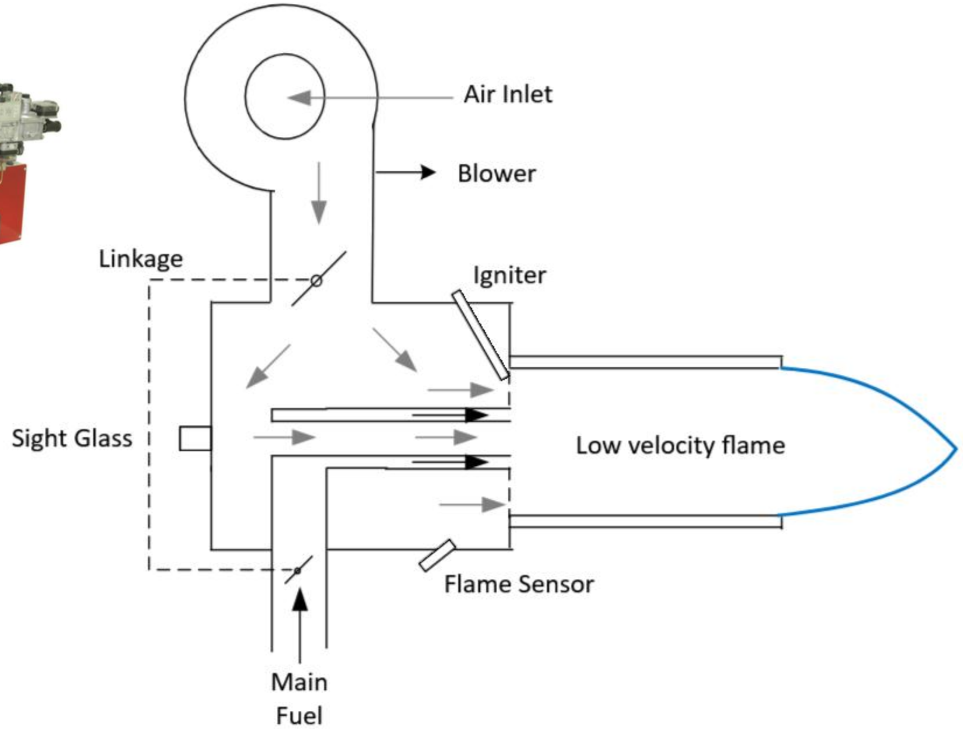




Typical for: Industrial furnaces, Atmospheric heaters

Increasing H_2: Impacts size of flame/reaction zone, *can* increase T_{flame}/S_L, but impacts are equipment specific on flame, heat transfer, air flow, NOx emissions – suitable for 100% H2

Air-Heating / PP Example



Typically for: Dryers and Process Ovens, Certain Low NOx equipment (e.g Air-staged), Radiant Tube Heaters

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

Overview of H_2 Basics – Industrial Burners

Outcome of the Technical Review

- **Key Takeaway**: **H_2-ready solutions are limited but exist**, project team can build on for conversions

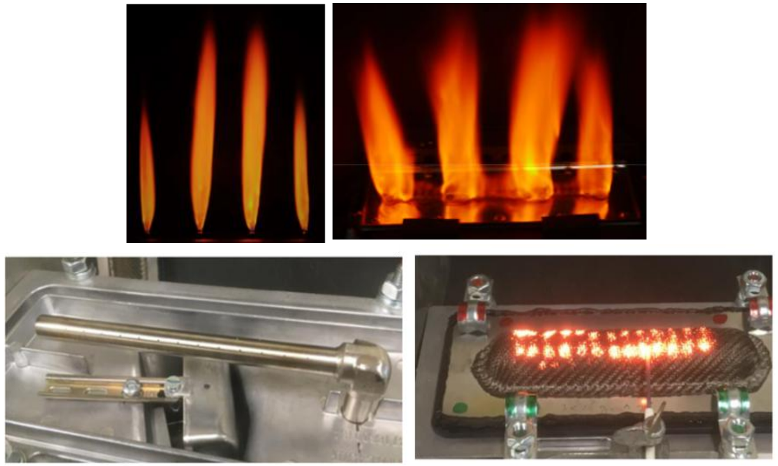
Biggest challenges of practical H_2 combustion are **flashback** and **detonation**

Option #1) Diffusion flames

- Fuel/air mix at flame front, very stable flame, though large rxn zone => higher NO_x
- Avoid flashback with P_{nozzle}/V_{fuel}

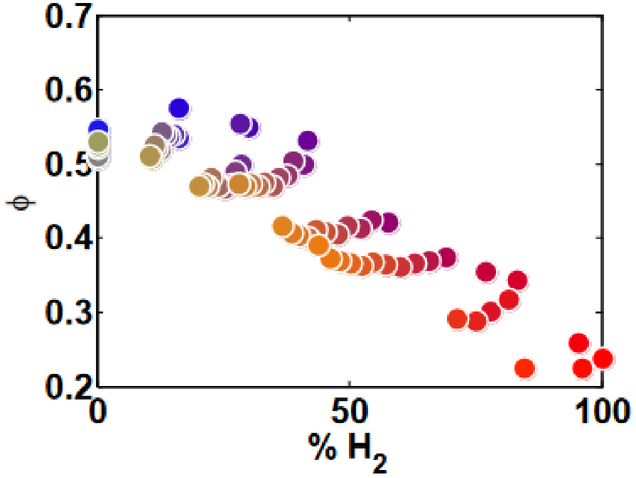
Option #2) Partial/Full Premix

- Preferred in closed chambers, for NOx and compact heat transfer
- Industry splits on pre vs. post mix for blowers, detonation risk
- Flashback mitigation with higher $V_{fuel/air}$ by operating **ultra lean**
  - λ can increase >3X vs. CH_4, increasing $V_{fuel/air}$ & reducing T_{flame}

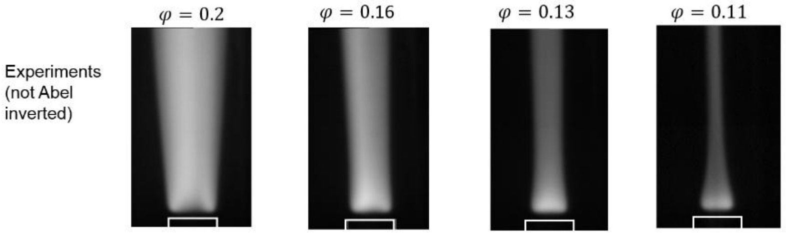


Source: Hy4Heat (UK, Top) and Gasterra (NL, Bottom)

LBO for Experimental GT*



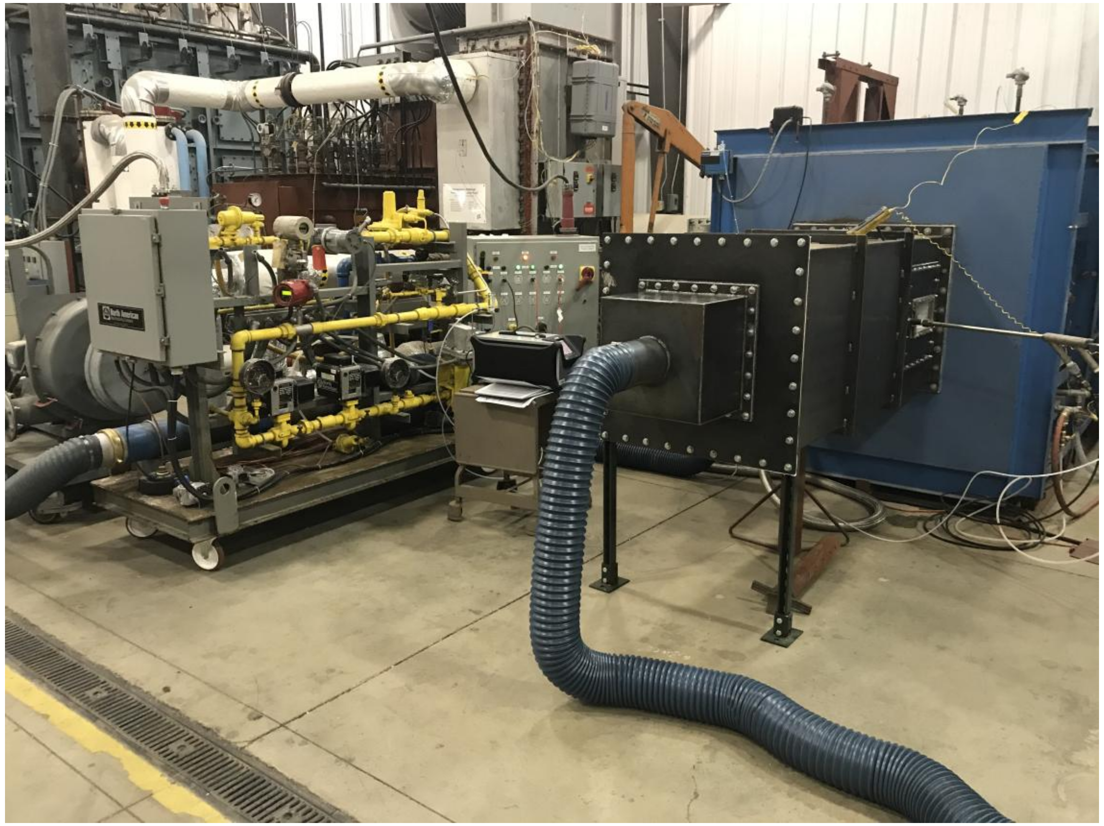
Ultra Lean H_2 Premix Flames**



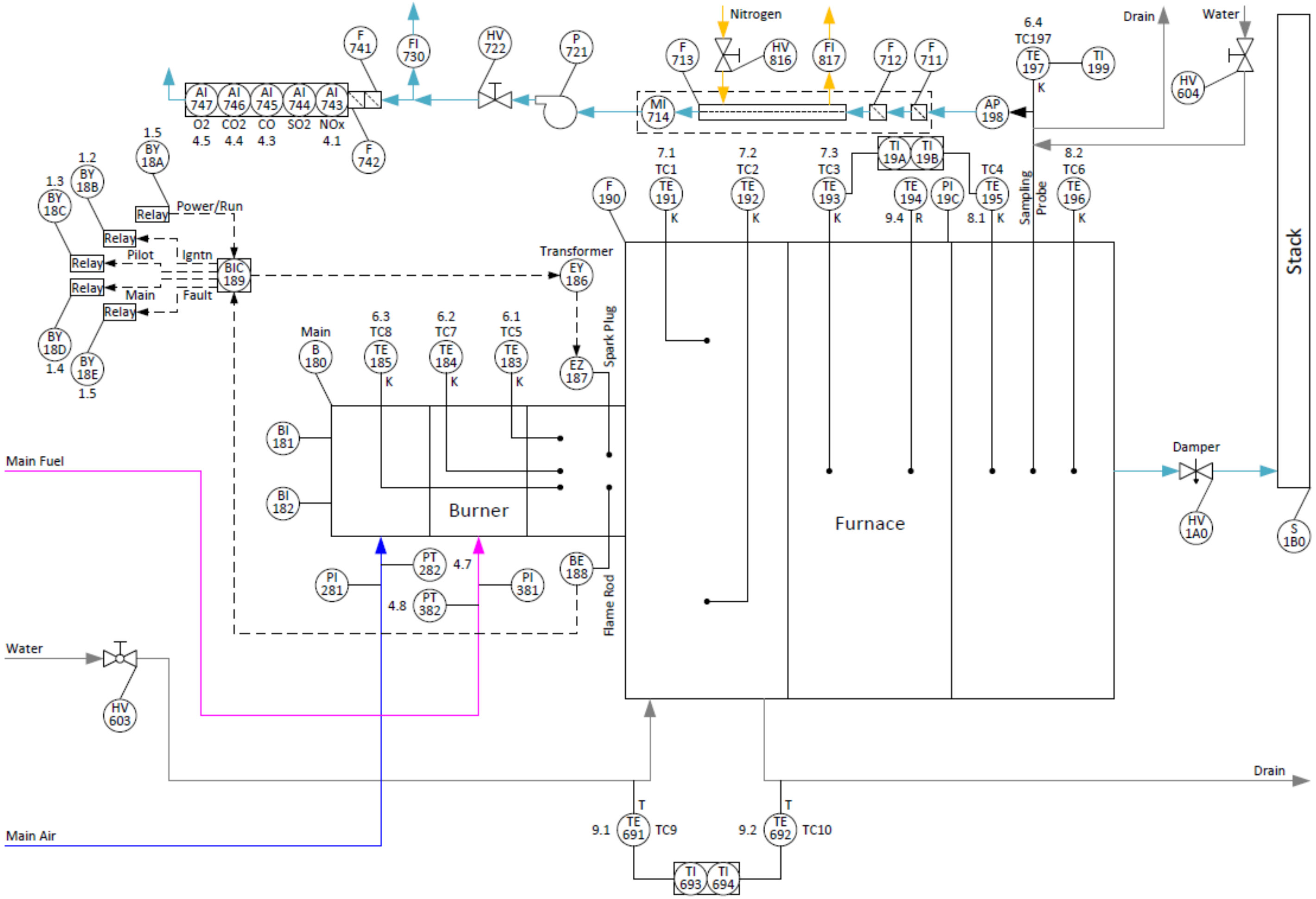
*Liewen and Zinn, 2007 (link) // **FH Vance et al. 2021 (link)

Industrial Test Furnace

Test sequence	Fuel	% Volume (NG – H_2)	Test type
Test 1	Natural gas only	100 - 0	Steady combustion/Gas ON/OFF test at fixed high and low fire rates
Test 2	Natural gas – H_2 blend	80 - 20	Cycling gas on-off test at fixed high fire rate or at manufacturer recommended light off rate
Test 3	Natural gas – H_2 blend	Increase H_2 from 20% until any issue*	
All remaining tests	Natural gas – H_2 blend	H_2 blend within safe upper limit*	All remaining test types (steady combustion, dynamic blending)

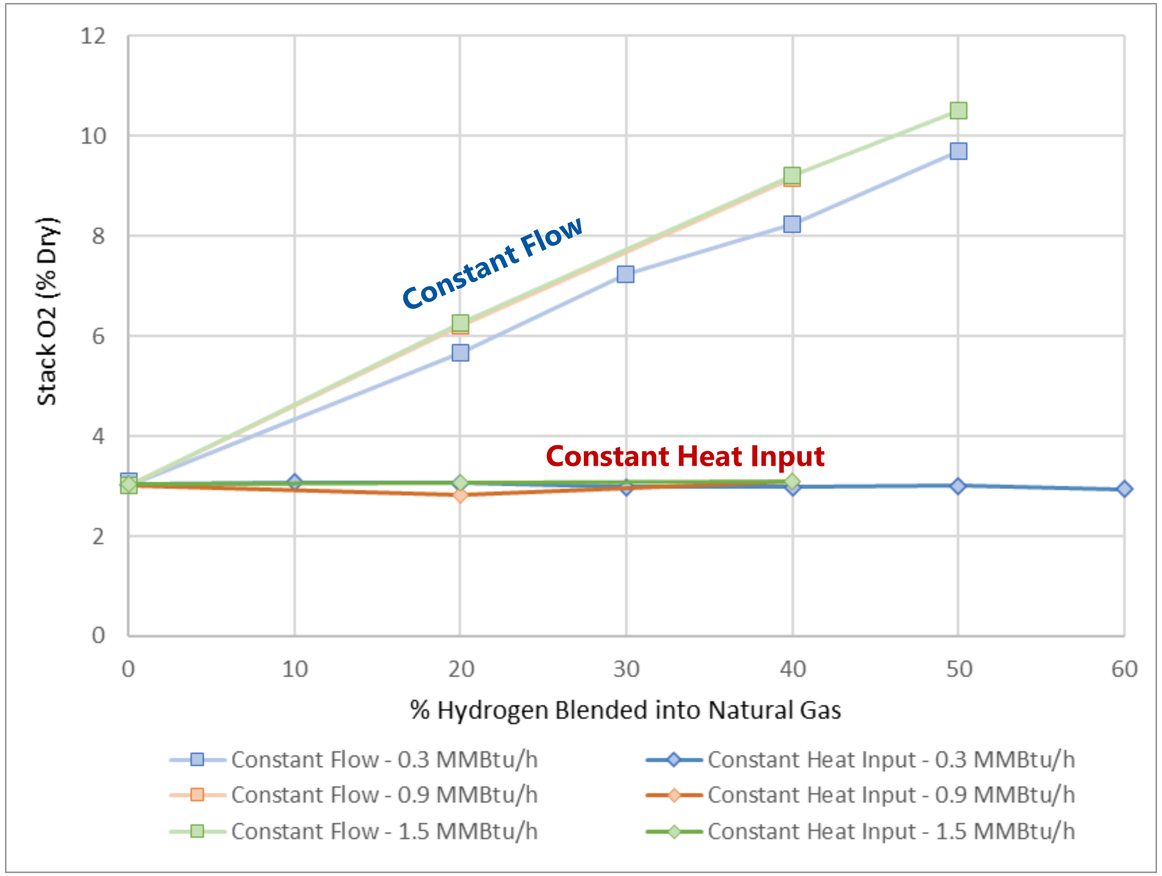


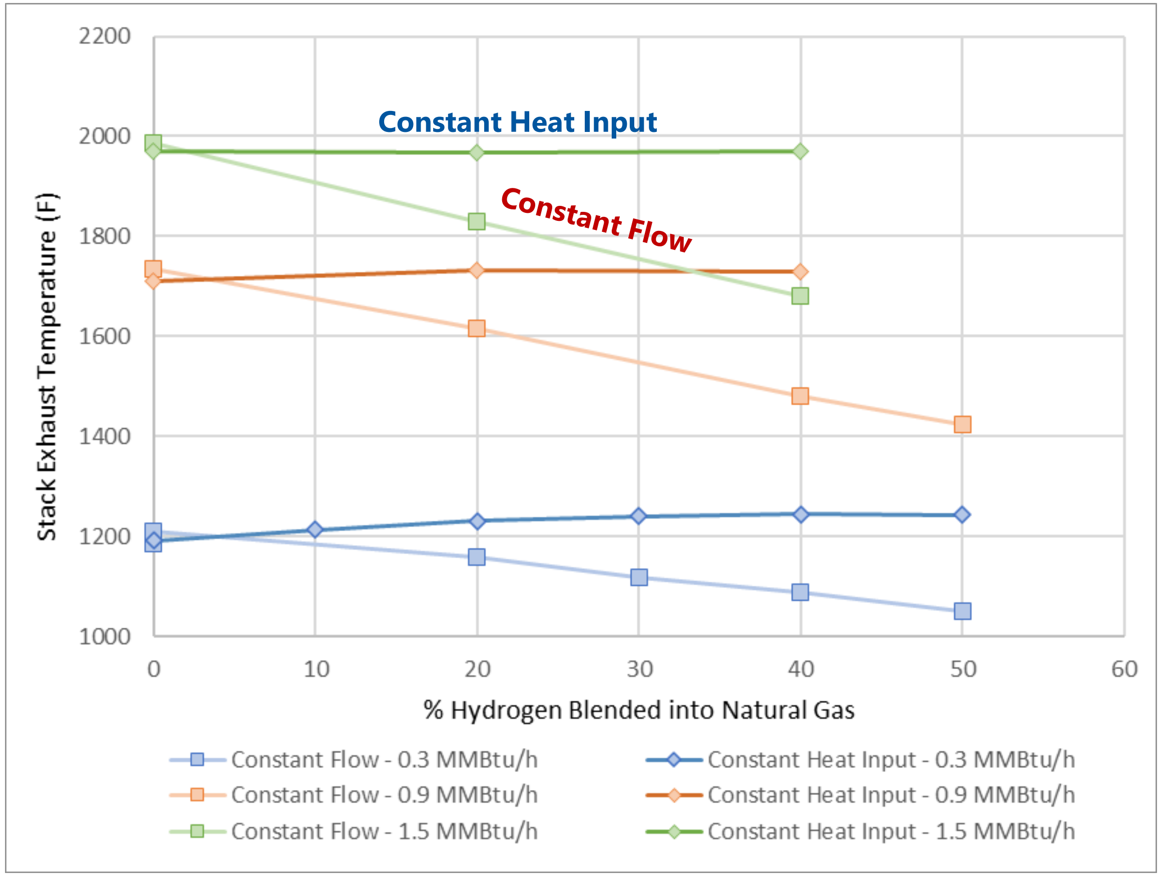
Industrial Test Furnace



Constant Flow vs. Constant Heat

Industrial Burner Example = Nozzle-mixed Non-Premixed (Burner #1)





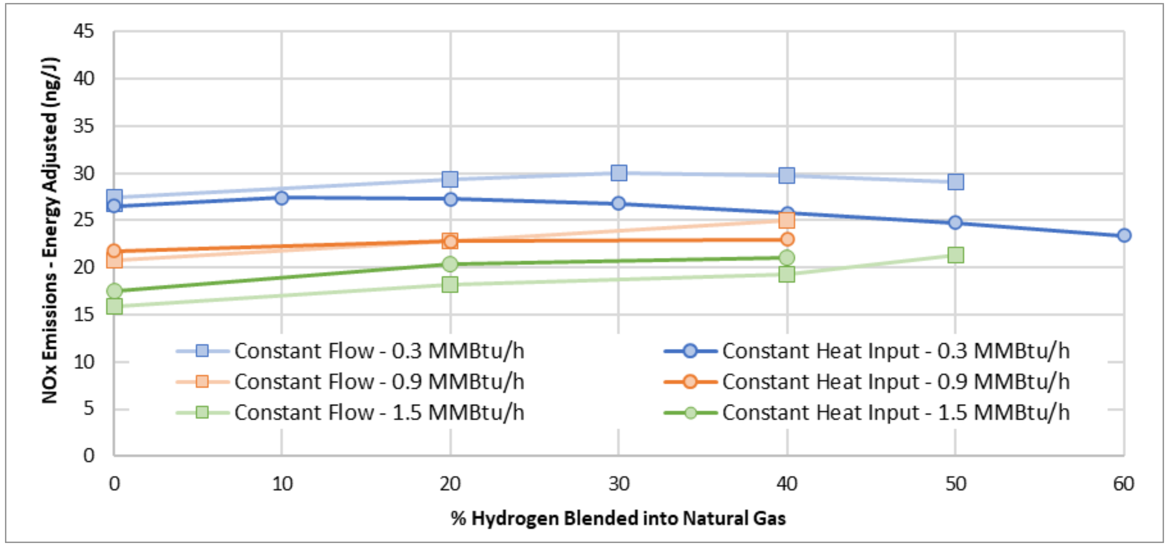
Constant Flow = Set for NG, shift fuel from there
Constant Heat = Continually increase flow at constant A/F ratio to maintain heating rate

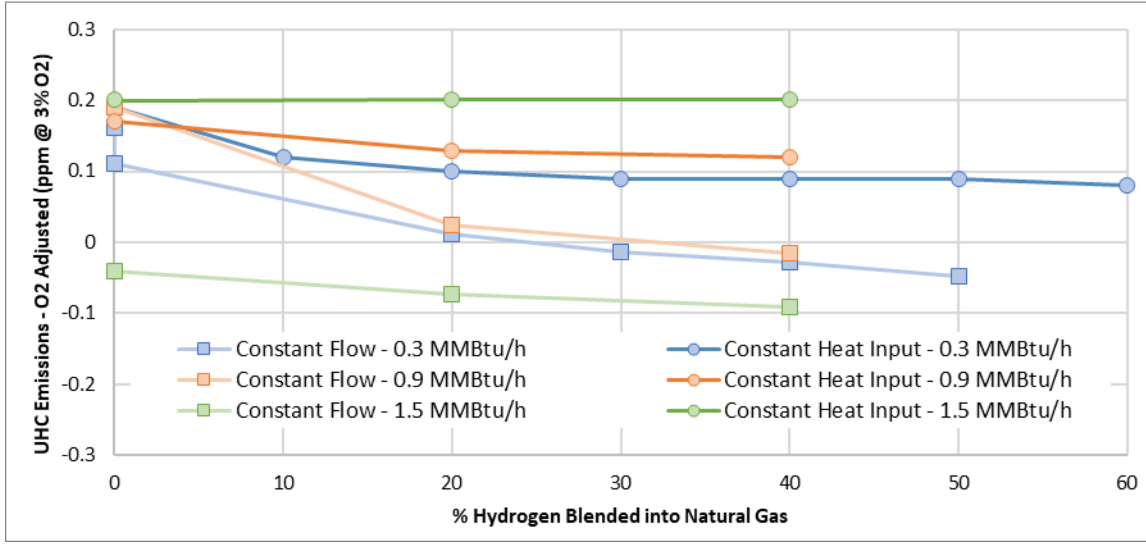
Industrial Furnace / Oven / Kiln

Preliminary Results (Industrial Furnace): Selected Results (NOx Emissions & CH_4 Slip)

GTI testing of industrial furnace burners, **<u>nozzle-mixed burner</u>** here, shows stability with "slug" tests and ~flat impact on NOx emissions and declining CH_4 emissions with increasing H_2

Slugging	Btu/h @ Constant P_{fuel} to Nozzle Mixed/High Velocity Burner					
Firing Rate	300,000		900,000		1,500,000	
$\%H_2$	up	down	up	down	up	down
0 to 20	✓	✓	✓	✓	✓	✓
20 to 30	✓	✓	--	--	--	--
20 to 40	--	--	✓	✓	✓	✓
0 to 30	✓	✓	--	--	✓	✓
0 to 40	✓	✓	✓	✓	✓	✓
0 to 50	✓	✓	--	--	--	--
0 to 60	✓	✓	✓	--	✓	✓
0 to 70	✓	✓	--	--	--	--
0 to 80	✓	✓	--	--	--	--



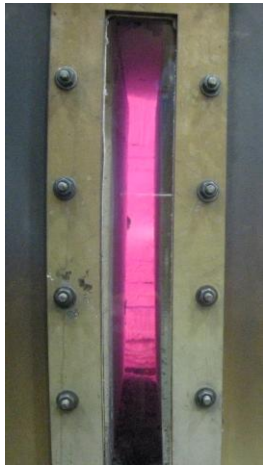


Preliminary Data – Subject to Change

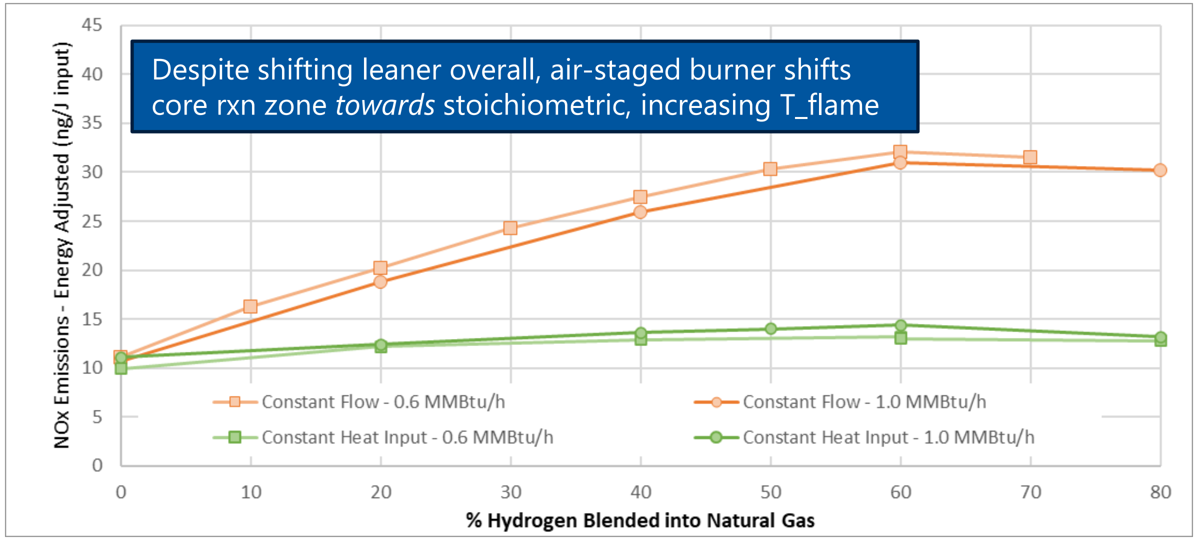
Industrial Furnace / Oven / Kiln

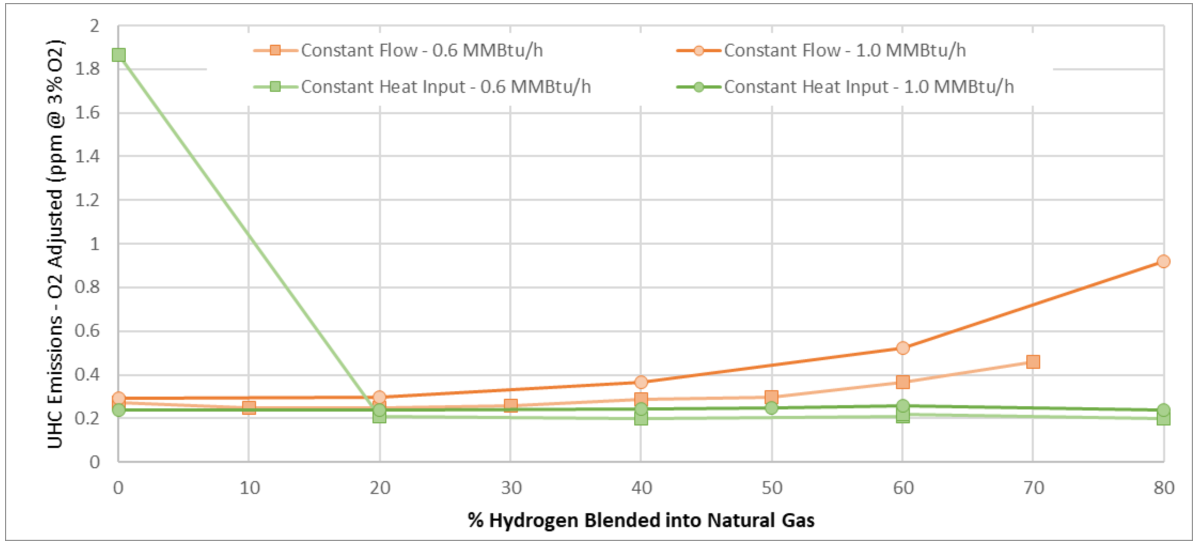
Preliminary Results (Industrial Furnace): Selected Results (NOx Emissions & CH_4 Slip)

Now **air-staged burner**, shows stability with "slug" tests but mixed impact on NOx emissions and CH_4 emissions with increasing H_2 – emissions increase w/o adj. for "on-rate" (shift lean)



Slugging	Tuned at 0%H2 vol			
FR	625,000 Btu/h		1,000,000 Btu/h	
%H2	up	down	up	down
0-20	okay	okay	okay	okay
20-40	okay	okay	okay	okay
0-40	okay	okay	okay	okay
0-60	okay	okay	okay	okay
0-80	okay	okay	okay	okay
0-50	--	--	okay	--





Data / Image Source: GTI Energy

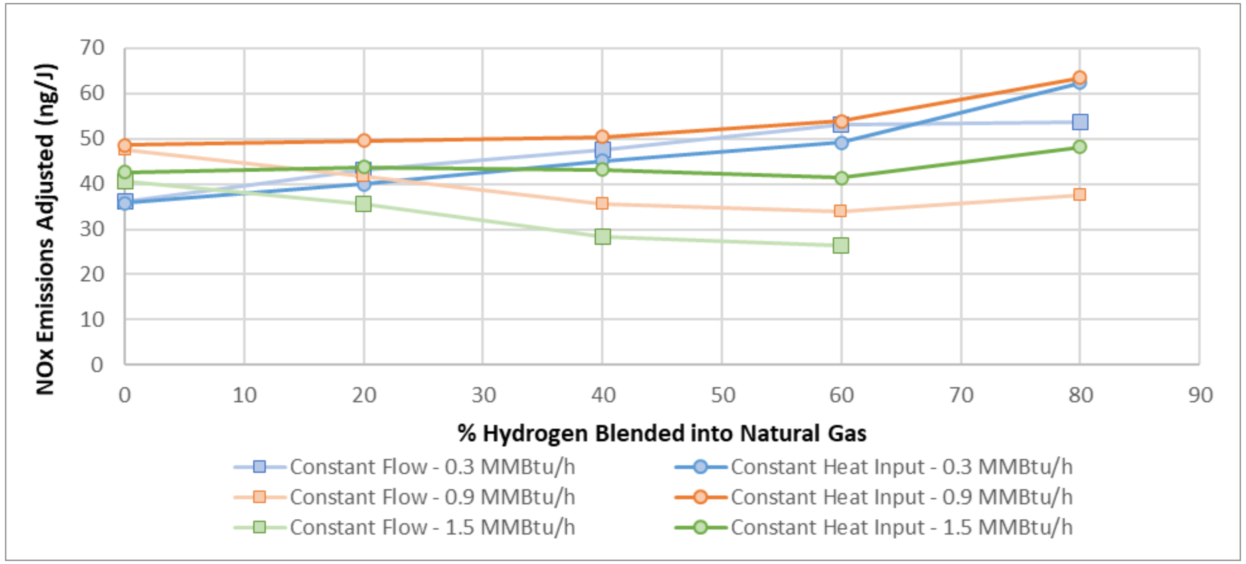
Preliminary Data – Subject to Change

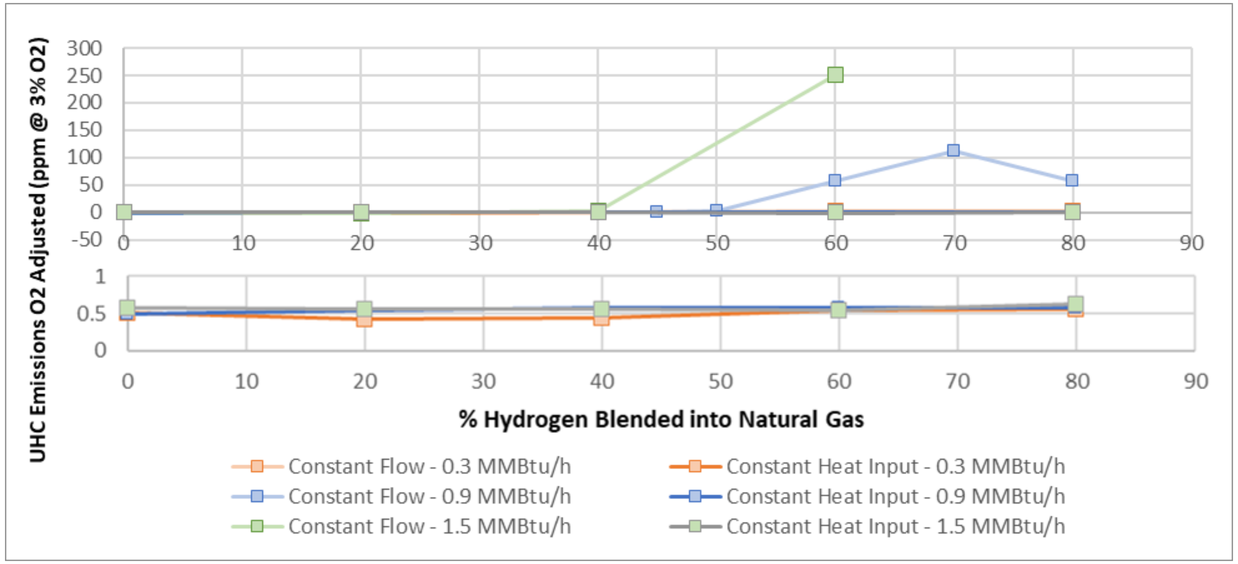
Industrial Furnace / Oven / Kiln

Preliminary Results (Industrial Oven/Kiln): Selected Results (NOx Emissions & CH_4 Slip)

Finally, **air-heating burner**, also shows stability with "slug" tests with moderate impact on NOx emissions increasing H_2 – for CH_4 emissions significant shift at high flows (const. flow), but negligible otherwise

FR	300,000 Btu/h		900,000 Btu/h		1,500,000 Btu/h	
%H2	up	down	up	down	up	down
0-20	okay	okay	okay	okay	okay	okay
20-40	okay	okay	okay	okay	okay	okay
0-30	--	--	okay	--	--	--
0-40	okay	okay	okay	okay	okay	okay
0-50	--	--	--	--	okay	--
0-60	okay	okay	okay	okay	okay	okay
0-70	--	--	okay	--	okay	--
0-80	okay	okay	okay	okay	okay	okay



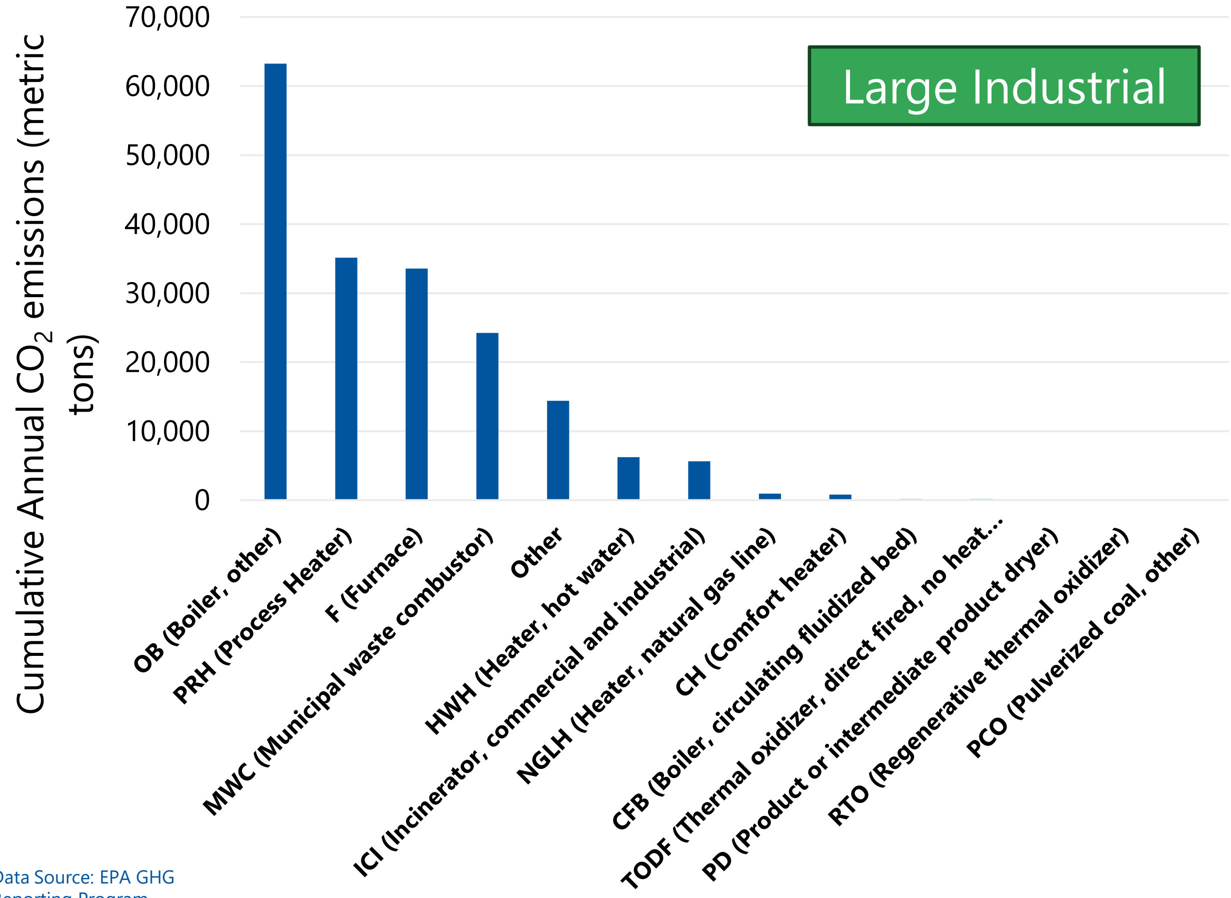


Data / Image Source: GTI Energy

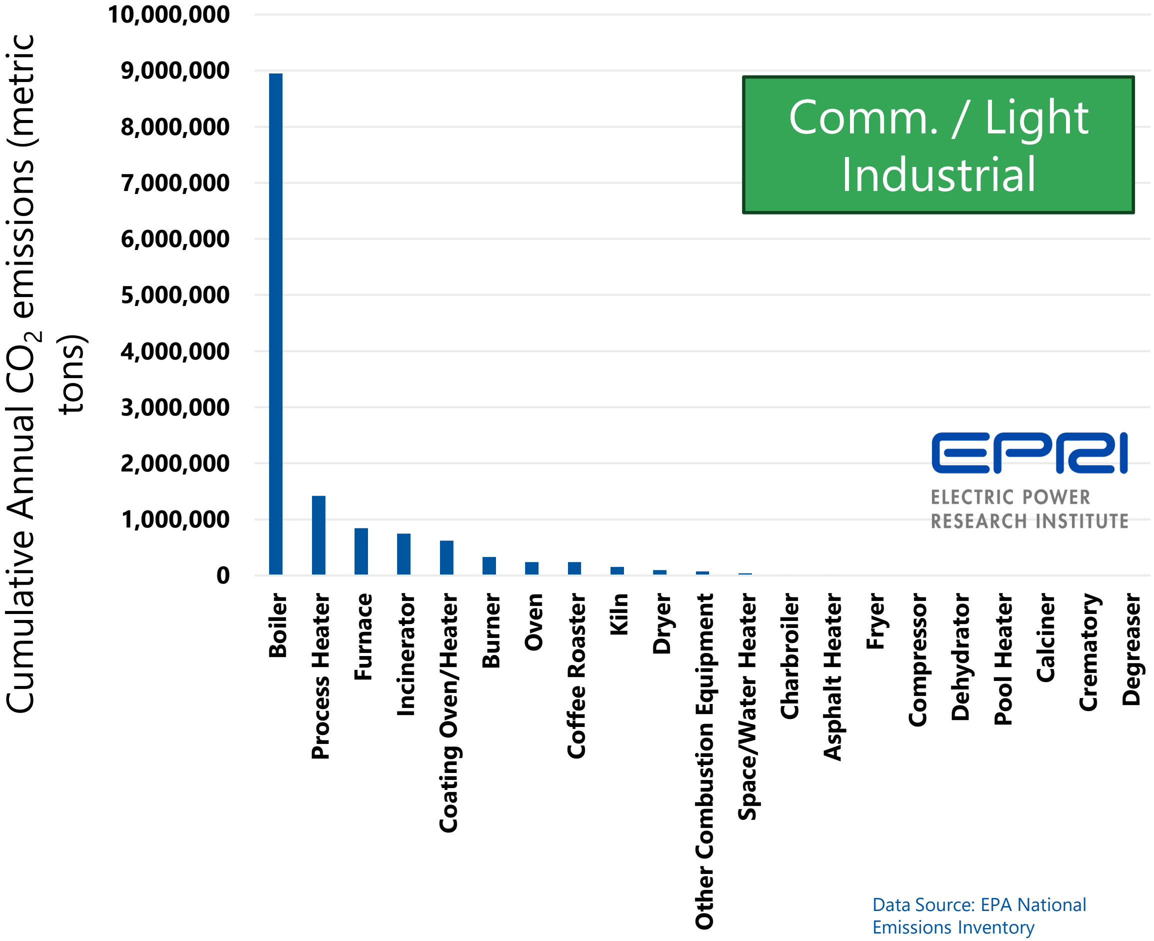
Preliminary Data – Subject to Change

Overview of H_2 Basics – Boilers & Water Heaters

Draft/Preliminary Results: Subject to Change



Data Source: EPA GHG Reporting Program



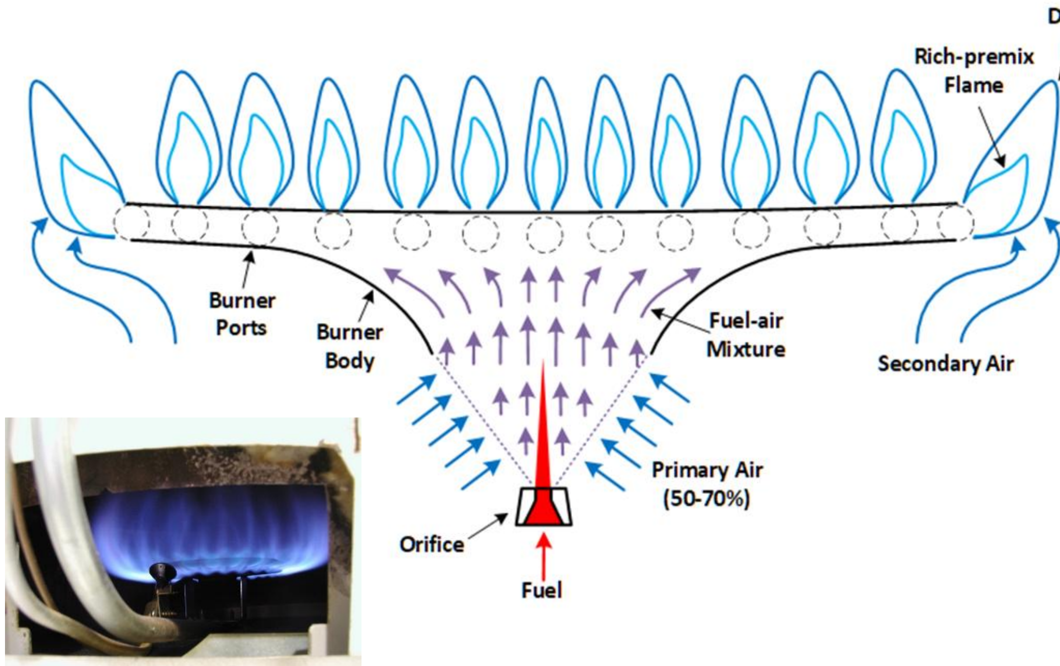
EPRI ELECTRIC POWER RESEARCH INSTITUTE

Data Source: EPA National Emissions Inventory

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

Overview of H_2 Basics – Boilers & Water Heaters

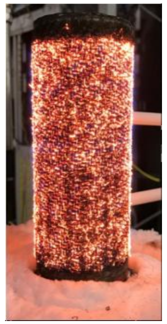
Partially-Premixed Example

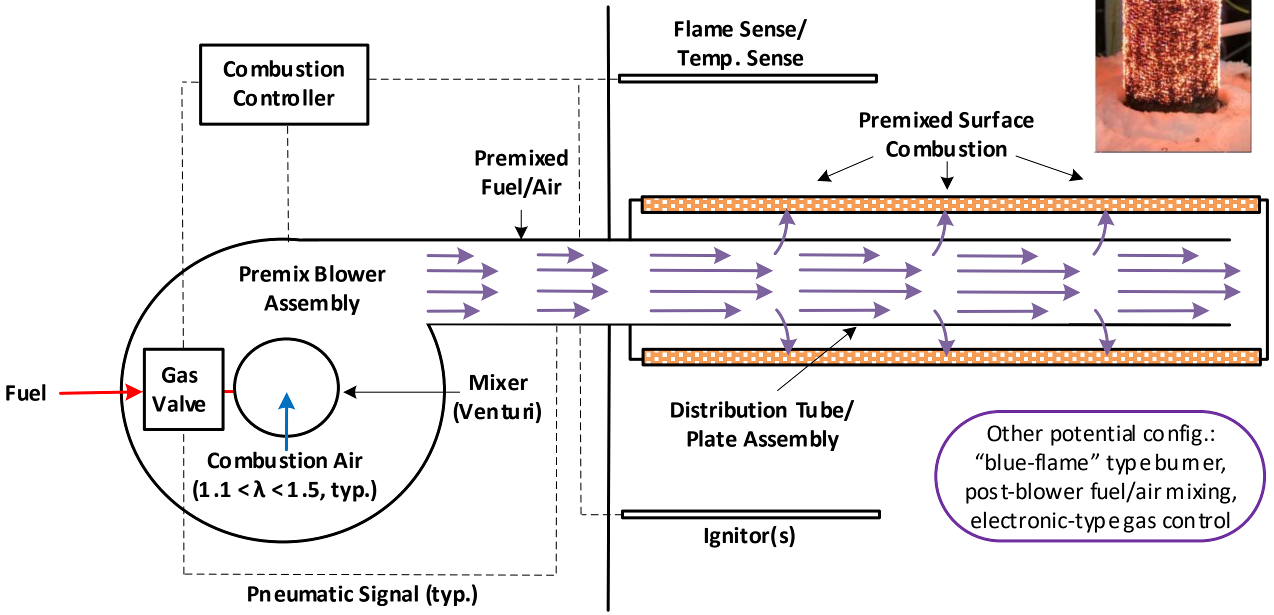


Majority: Storage-type Water Heating, Hot Water/Steam boilers, Process/Pool heaters

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

Premixed Example

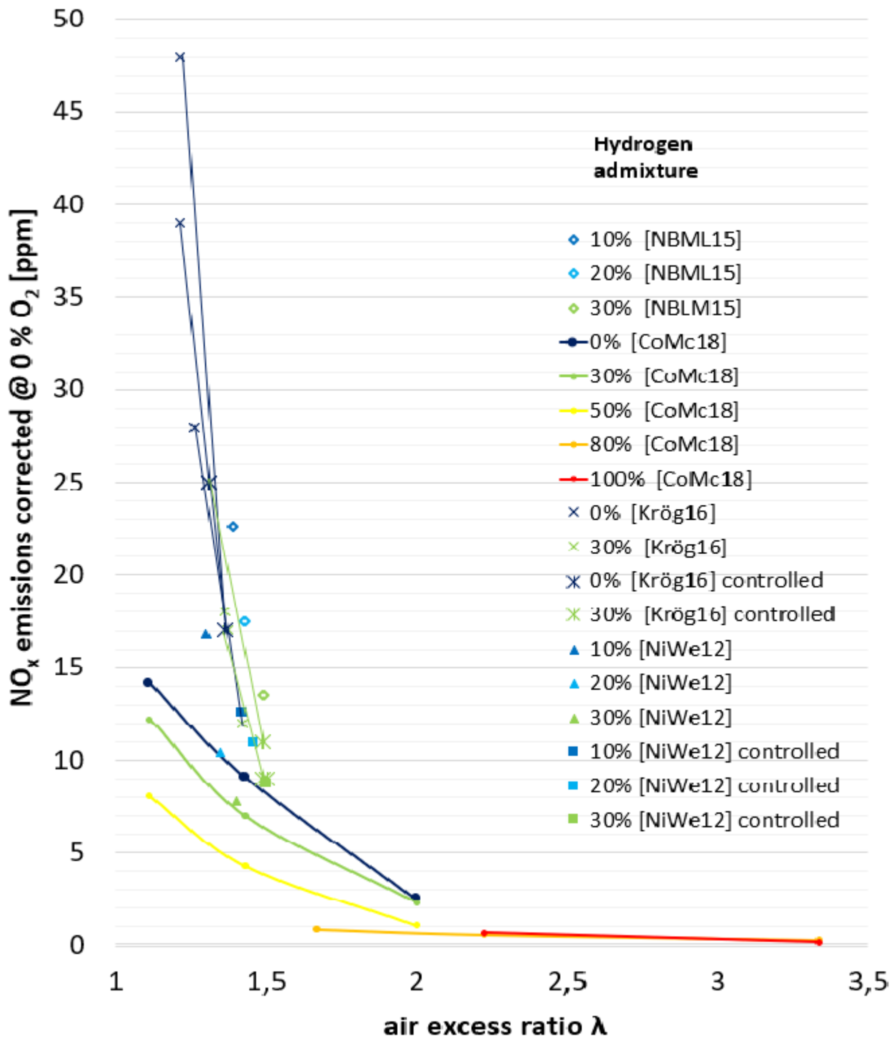




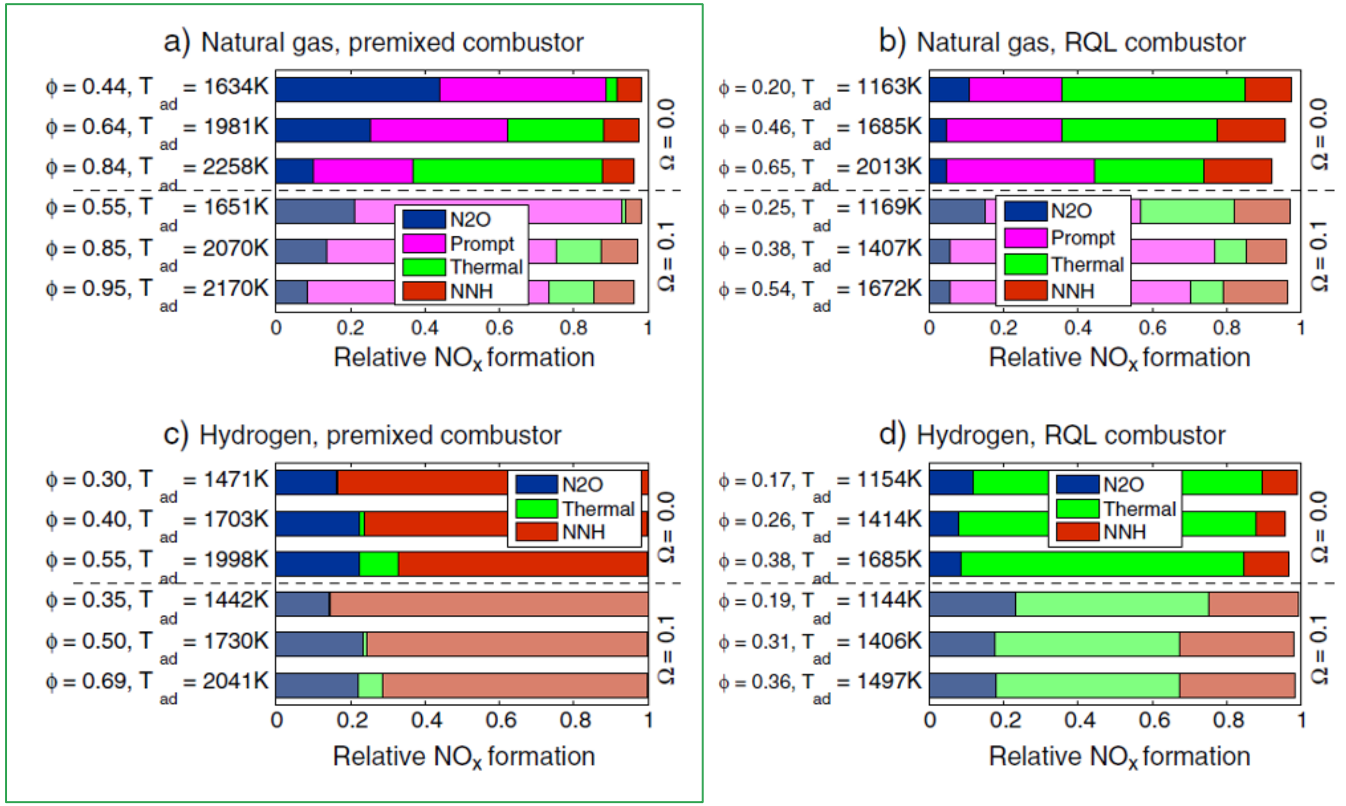
Majority: Tankless-type Water Heating, High-efficiency and/or Ultra-Low NOx products

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

Overview of H_2 Basics – Boilers & Water Heaters



Source: J. Schaffert, "THyGA - Impact of Hydrogen Admixture on Combustion Processes - Part II: Practice," https://thyga-project.eu, 2020.



Source: S. Göke et al. *Influence of steam dilution on the combustion of natural gas and hydrogen in premixed and rich-quench-lean combustors*, Fuel Processing Technology, Volume 107, 2013, Pages 14-22,

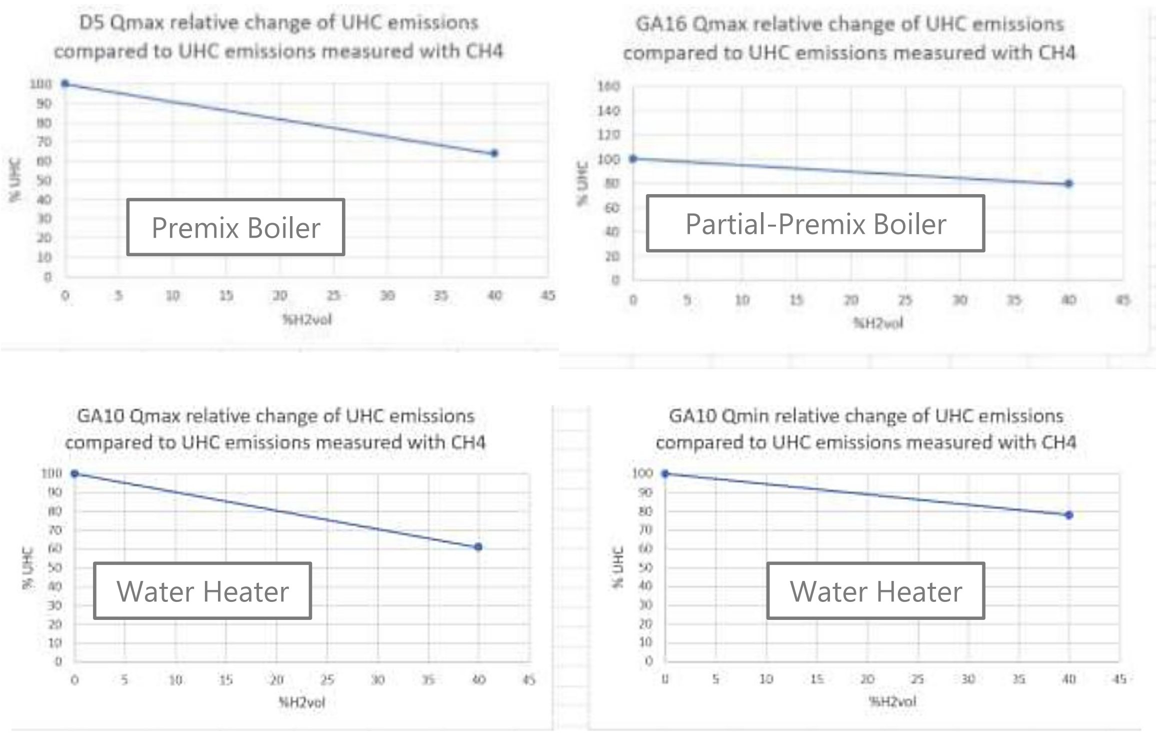
NOx emissions will depend on burner type, operating point, H_2-blending ratio, and other factors, and is primarily a strong function of λ

Overview of H_2 Basics – Boilers & Water Heaters

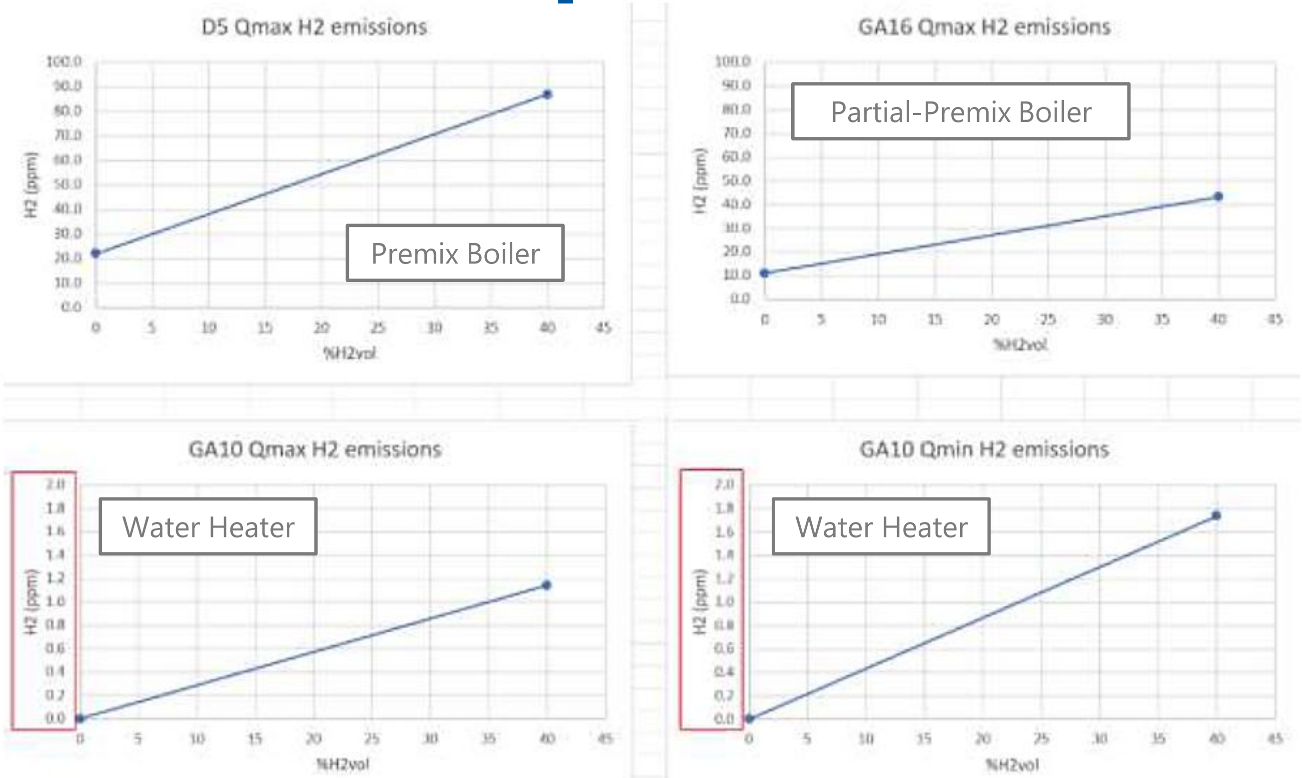
Fugitive Emissions (“slip”) from Burner – Boilers & Water Heaters

- **Very** limited H_2 emissions sampling from equipment - **THyGA*** project tested a range of equipment with up 40%-60% H_2 blends,
  - Unburnt fuel (UHC) emissions tend to decline with blending, H_2 emissions (limited test) increase

UHC (CH_4) Emissions



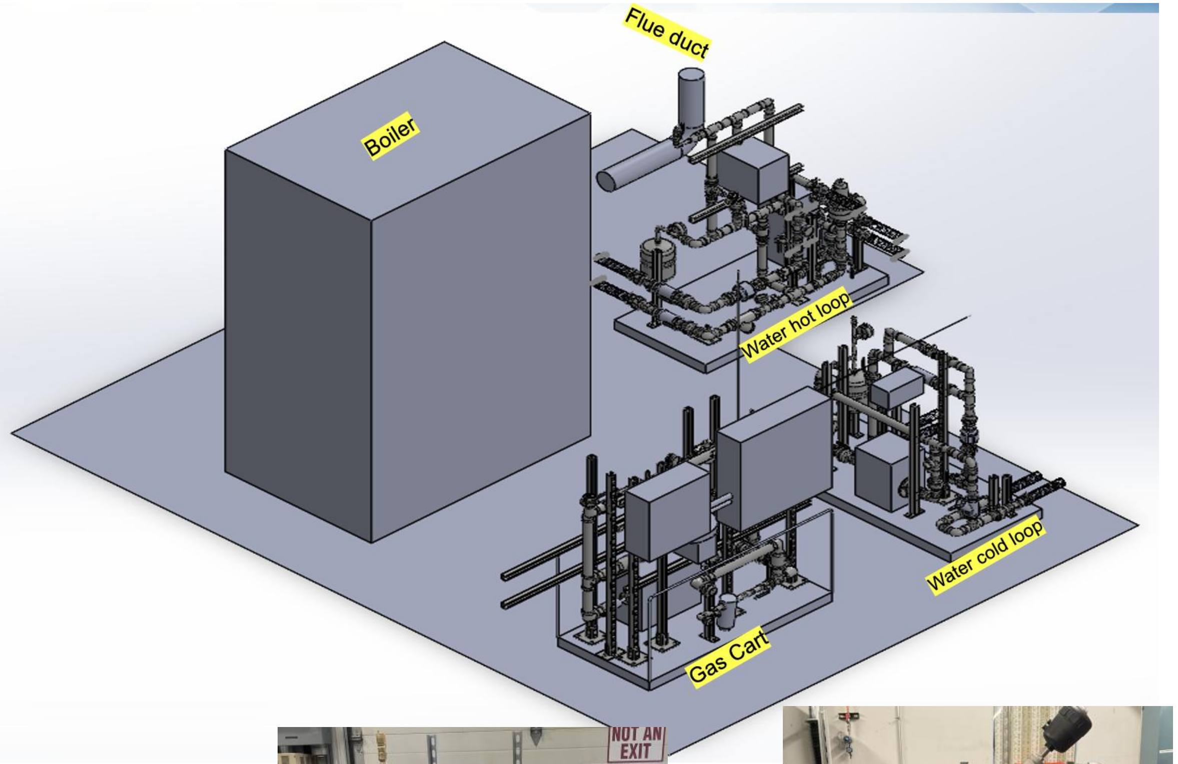
H_2 Emissions

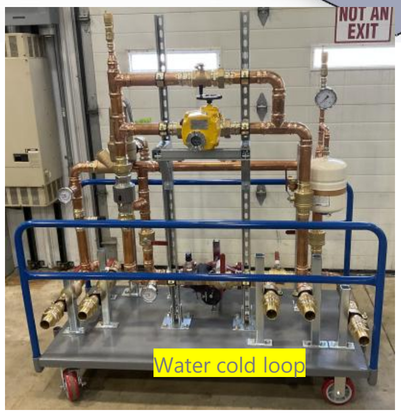


*Data Source – THyGA Project: https://thyga-project.eu/wp-content/uploads/20230512-D3.8-Report-on-the-impact-of-H2-concentrations-on-safety-efficiency-emissions-and-correct-operation-for-different-segments-of-appliances_light.pdf

Test Plan: Test boiler and experimental set up

	Boiler 1	Boiler 2
Max Input, MMBtu/h	1.6	1.0
Output, MMBtu/h	1.51	0.965
Modulation	20:1	10:1
Burner	Premixed	Premixed
Ignition	Pilot gas with spark plug	Direct Spark Ignition
Heat exchanger	Water tube	Fire tube
Condensing	Yes	Yes
Venting	Forced	Forced
Gas supply pressure, inch of water	4-10.5	3.5-13
Maximum water pressure, psig	160	160
Maximum water temperature, deg F	200	210
Electrical	120V/60Hz/1ϕ/8.1A	120V/60Hz/1ϕ/10A
Applicable Standards	ANSI Z21.13:22; CSA 4.9:22; ASHRAE 155	





Test Plan: Test water heater and experimental set up

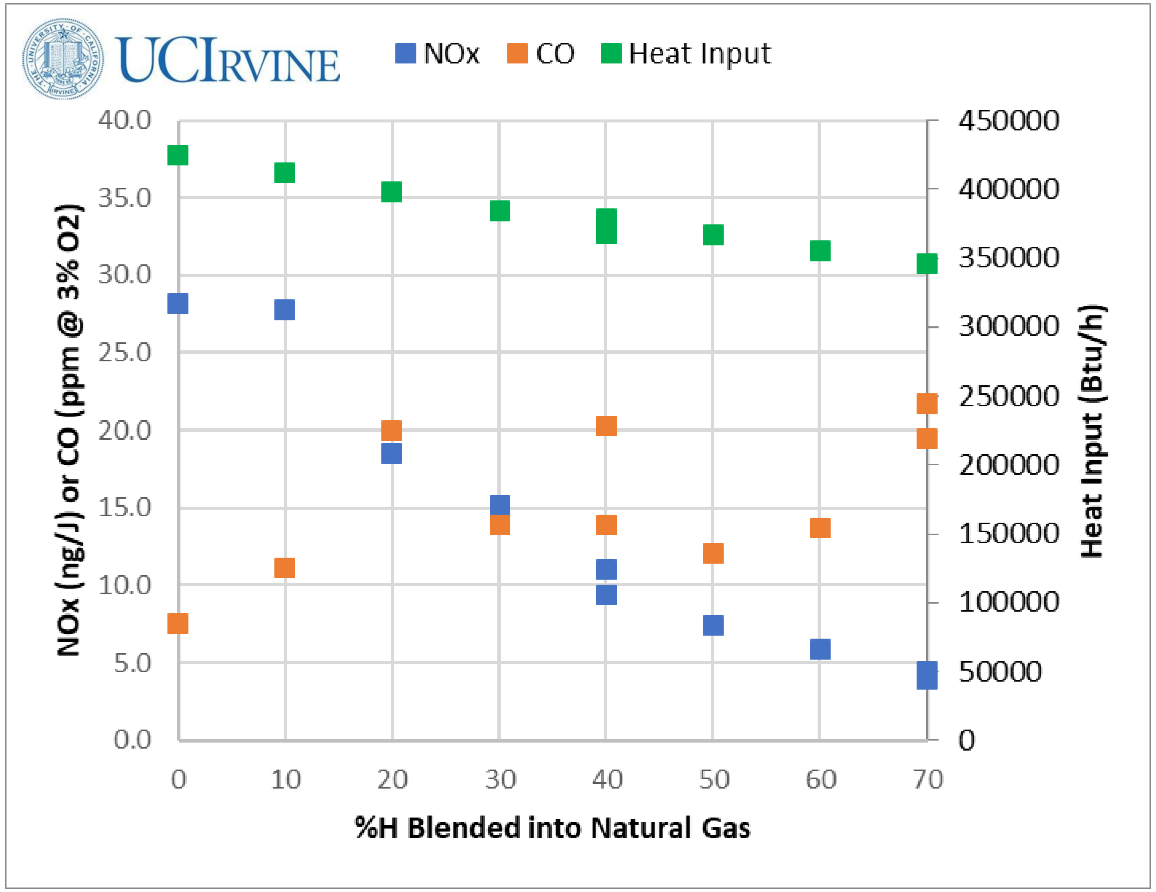
	Water Heater 1	Water Heater 2
Max Input, Btu/h	400,000	400,000
Storage, gal	100	120
Burner	Premixed	Premixed
Ignition	Direct spark ignition	Direct Spark Ignition
Condensing	No	Yes
Venting	Atmospheric	Forced
Gas supply pressure, inch of water	Up to 14	Up to 14
Maximum water pressure, psig	150	160
Maximum water temperature, deg F	180	180
Electrical	120V/60Hz/1ϕ/2A	120V/60Hz/1ϕ/5A
Applicable Standards	ANSI Z21.10.3; CSA 4.3; ASHRAE 118.1	

Boilers & Water Heaters: Test Planning

Test sequence	Fuel	% Volume ($NG – H_2$)	Test type
Test 1	Natural gas only	100 - 0	Steady combustion/Gas ON/OFF test at fixed high and low fire rates
Test 2	Natural gas – H_2 blend	85 – 15	Cycling gas on-off test at fixed high fire rate or at manufacturer recommended light off rate
Test 3	Natural gas – H_2 blend	Increase H_2 from 15% until any issue*	
All remaining tests	Natural gas – H_2 blend	H_2 blend within safe upper limit*	All remaining test types (steady combustion, dynamic blending)

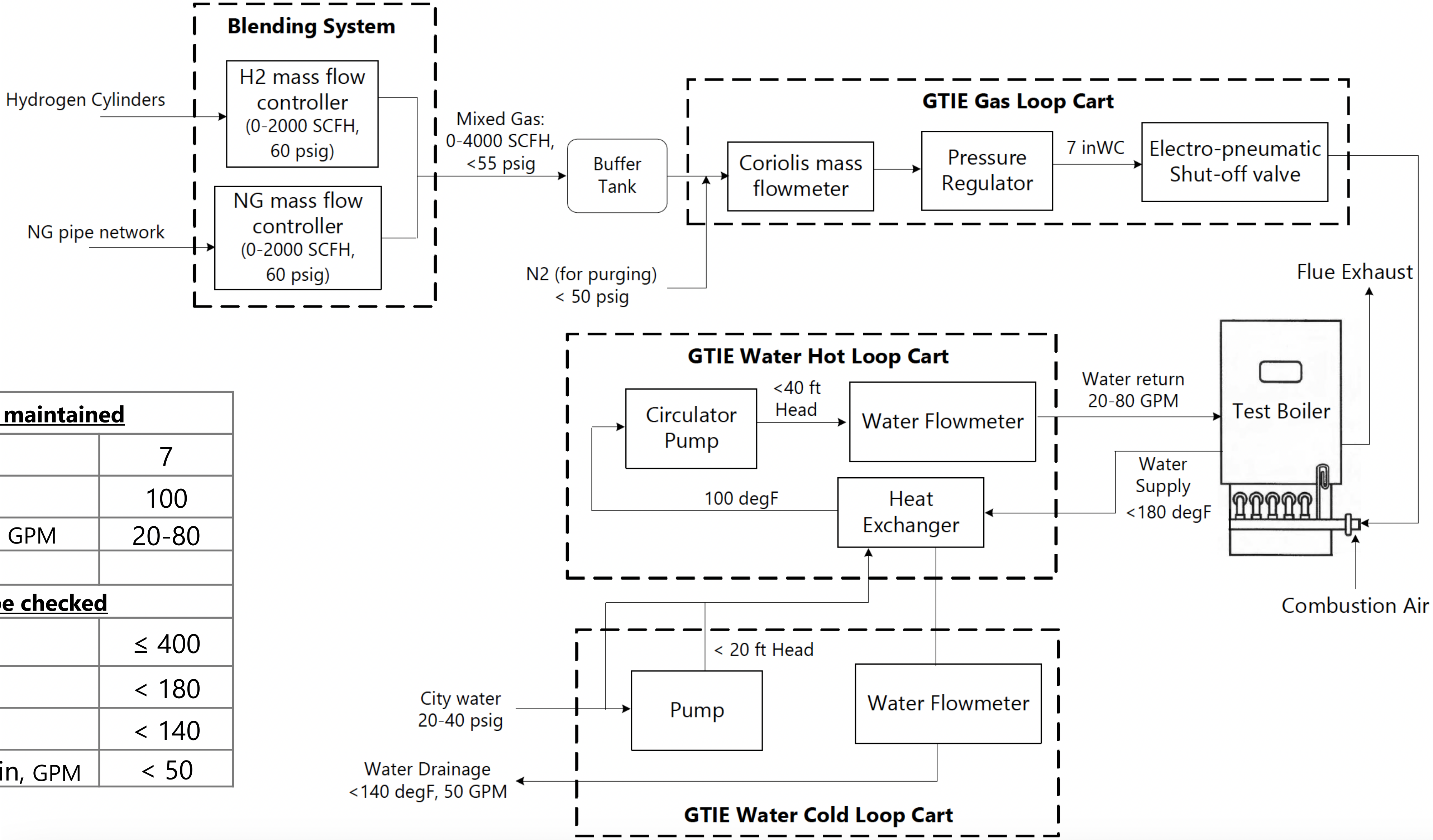
Unstable operation indicator:

- Excessive emissions of CO (> 400 ppm air free)
- Unstable ignition, delayed ignition, flash back, flame extinction, etc.
- Excessive appliance noise (dB relative to baseline)
- Excessive burner and boiler surface temperatures.



For water heaters tested, GTI and UC Irvine are performing interlab testing to analyze potential for lab biases, above is preliminary data on comm. water heater @ UCI which will be shipped to GTI soon for testing later this year.

Boilers & Water Heaters: Process flow diagram



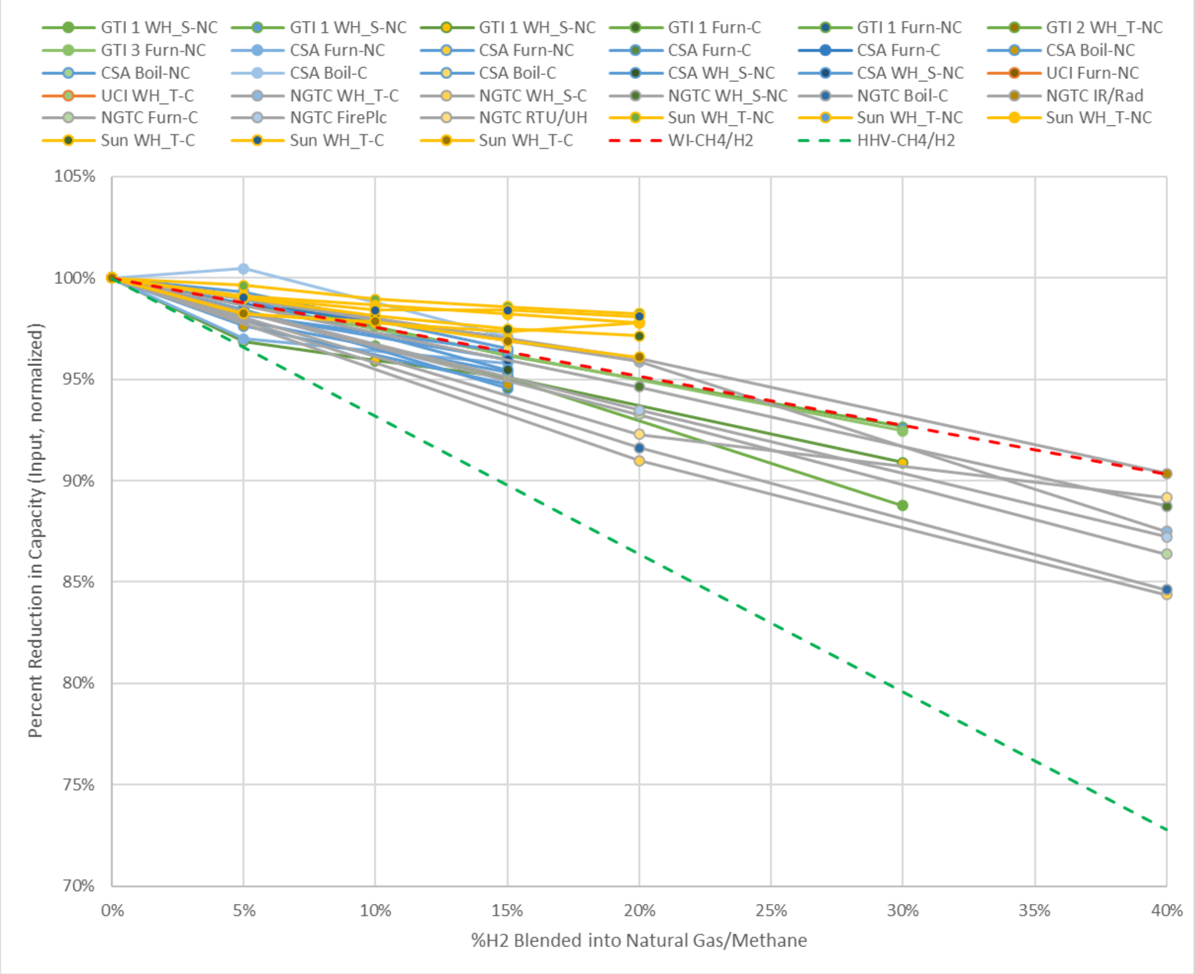
Parameters to be maintained	
$P_{Gas\ supply}$ (inches of water)	7
$T_{Water\ return}$ (degF)	100
Hot loop water flow rate, GPM	20-80
Parameters to be checked	
$CO_{air\ free}$ (ppm)	≤ 400
$T_{Water\ supply}$ (degF)	< 180
$T_{Water\ drain}$ (degF)	< 140
Cold loop water flow drain, GPM	< 50

Boilers & Water Heaters: Testing Results

Expected impact – Capacity / Stability

- Capacity impact is common, within **5% of Wobbe Index**, HHV (1/3) reduction is not predictive
  - This translates to 5%-10% reduction expected in range of nominal blends
  - Measurable impact on efficiency observed with blending (up/down), but typ. +/- 2%
- – Upper stability limits typ. >50%, but vary by appliance
- – Current test program will expand to this dataset with larger C&I equipment

EQUIPMENT: Furn = furnace, WH_S/T = storage/tankless water heater, Boil/B = boiler, IR/Rad = infrared/radiant heater, FirePlc = fireplace, RTU/UH = RTU/Unit Heater
EFFICIENCY: C = Condensing, NC = Non-condensing



Source: THyGA Project, https://thyga-project.eu/wp-content/uploads/20230512-D3.8-Report-on-the-impact-of-H2-concentrations-on-safety-efficiency-emissions-and-correct-operation-for-different-segments-of-appliances_light.pdf // GTI Meta-study

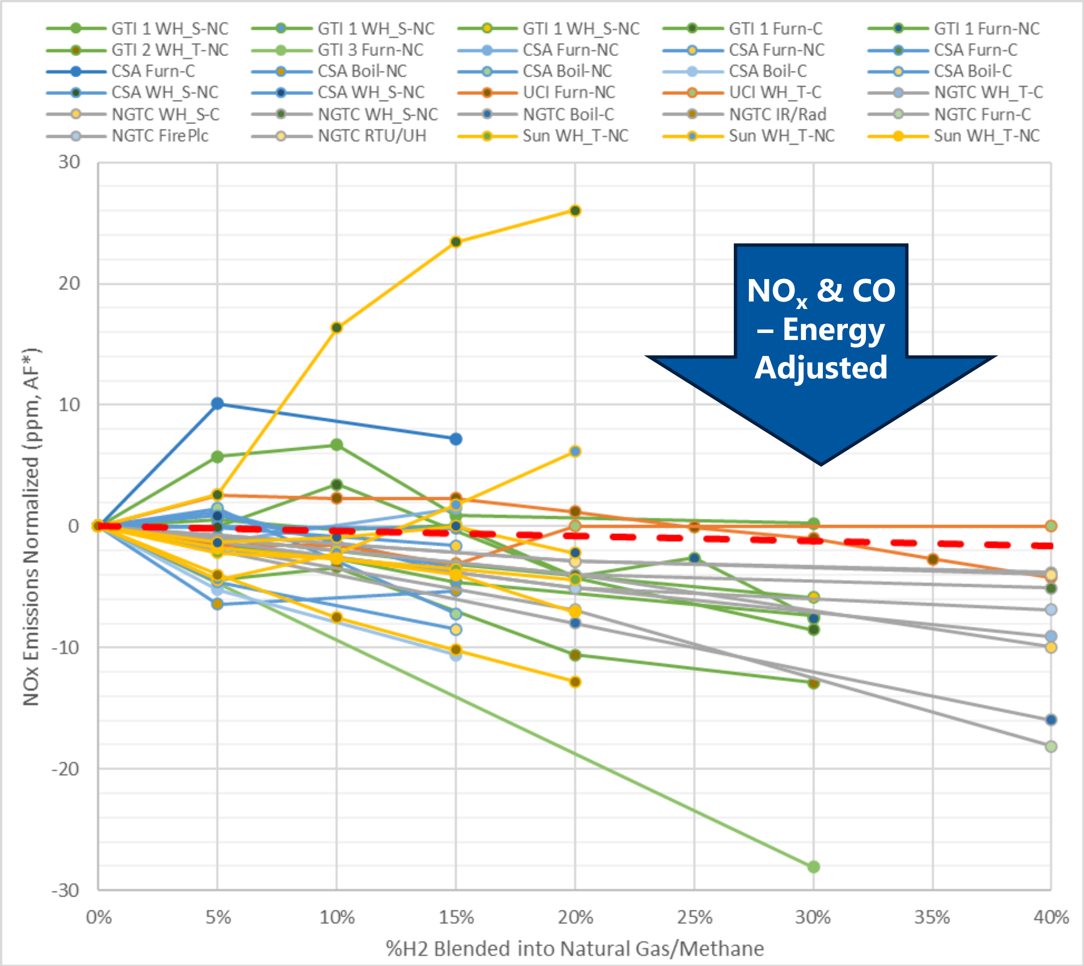
Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

Boilers & Water Heaters: Testing Results

<u>Expected impact - NOx/CO emissions</u>

- Population-weighted average of CO and NOx emissions decrease with H_2 addition
  - For NOx, hotter $T_{adia,flame}$ by ~265°F is offset by shift to leaner λ. H_2 requires ¼ the air vs. CH_4
  - For CO, the shift leaner helps along with reduced fuel-bound carbon for partial oxidation
- Current test program will expand to this dataset with larger C&I equipment

EQUIPMENT: Furn = furnace, WH_S/T = storage/tankless water heater, Boil/B = boiler, IR/Rad = infrared/radiant heater, FirePlc = fireplace, RTU/UH = RTU/Unit Heater EFFICIENCY: C = Condensing, NC = Non-condensing



Source: THyGA Project, https://thyga-project.eu/wp-content/uploads/20230512-D3.8-Report-on-the-impact-of-H2-concentrations-on-safety-efficiency-emissions-and-correct-operation-for-different-segments-of-appliances_light.pdf // UCI (Res. WH only), https://www.sciencedirect.com/science/article/pii/S036031992300722X // GTI Meta-study

Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

A.O. Smith
Innovation has a name.

Decarbonizing Water Heating with Hydrogen – OEM Perspective

02/11/2025

—

Steve Memory

Introduction

- Significant recent scale up in interest and investment by NA utilities in both pipeline distribution and end use equipment with H2/HG blends
  - several pilots underway in NA and Europe looking at blending up to 20% hydrogen into gas grids
  - many countries see blended hydrogen as an intermediate step to 100% hydrogen in the future

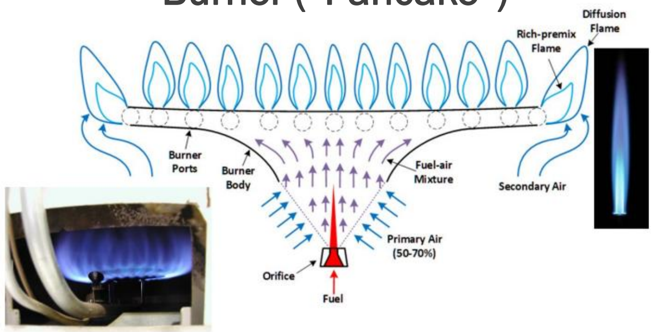
- OEM's have some logical concerns when using H2/NG blends for different burner types, especially partial premix (majority of water heaters):
  - Existing (legacy) equipment malfunction
  - Unsafe operating temperatures
  - Safety concerns (flashback)
  - Effect on efficiency
  - Increase of NOx or CO

Recent studies are helping to address some of these concerns

Noteworthy Recent NA Studies on H2 Enriched NG in WH's: Summary

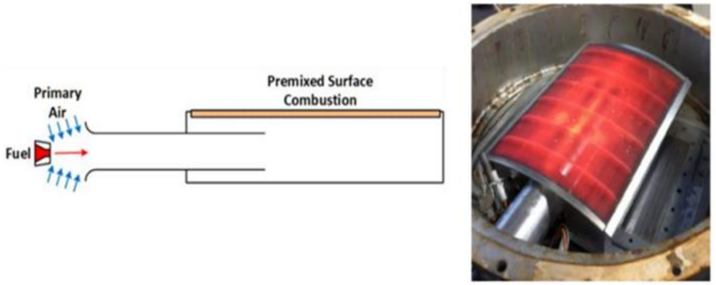
- CSA led an experimental study of blends containing up to 15% H2 on partially premixed water heating appliances [1]:
  - For partially premix (atmospheric, ULN) storage WH's => "passed ignition and BOC testing (per CSA/ANSI Z21)"
  - "Overall, (partially pre-mix) appliances showed no major operable issues (for HENG blends up to 15%)"
- AHRI conducted a risk assessment using extensive SOTA research on whether US gas appliances remain safe if they are fueled by hydrogen enriched NG [2]:
  - "Current production appliances will withstand the increased propensity to light-back without incident at a 20% blend"
  - "There is a concern with older appliances (legacy appliances) which have been out of production for many years"
  - Unlike the EU, US appliances have not been tested for light-back with 23% H2 limit gas (G222) at the time of certification"
  - "Theoretical indications and initial evidence suggests that it should be safe to inject up to 20% H2 into the US gas main without significant risk"
- GTI conducted an experimental analysis for partially premixed combustion equipment (majority of water heaters) [3]:
  - Testing of atmospheric low and ULN burners plus in situ tests in three WH's with NG, 100% methane, 5-30% H2
  - No combustion stability impacts – flashback, flame lift, high CO; dominant impact of H2 blending is increase of excess air resulting in lower NOx and surface temperatures; limited visual change to flames
  - Input rate decreased by up to 11%, NOx emissions stayed flat or decreased (AF), efficiency varied ↓ or ↑ by <1.5% for standard and ULN respectively
- UCI compiled many works on mixing of H2/NG on residential partially premixed WH's [4]:
  - The % decrease in NOx and NO is greater for ultra low NOx devices (<10 ng/J) compared to conventional "pancake burners"
  - ULN devices appear to be able to accept greater amounts of H2, above 70% in some cases, without modification

Partially Premixed Self-Aspirating Burner ("Pancake")



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

Fully Premixed Self-Aspirating Burner



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

1. *Appliance & Equipment Performance with Hydrogen-Enriched Natural Gases, CSA Group, 2021*
2. *Assessment of Hydrogen Enriched Natural Gas, AHRI Report #8024, Needley & Peronski, 2021*
3. *Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance*, Glanville et al., Energies, 2022
4. *A compilation of operability and emissions performance of residential water heaters operated on blends of natural gas and hydrogen*, Basinger et al., Int. J. Hydrogen Energy, 2023

Internal Work on Partial Premix Residential Units (Up to 30% H2)

<u>Residential Partial Premix Products Tested</u>

a) 30-gallon unit with a standard atmospheric 30,000 Btu/hour burner

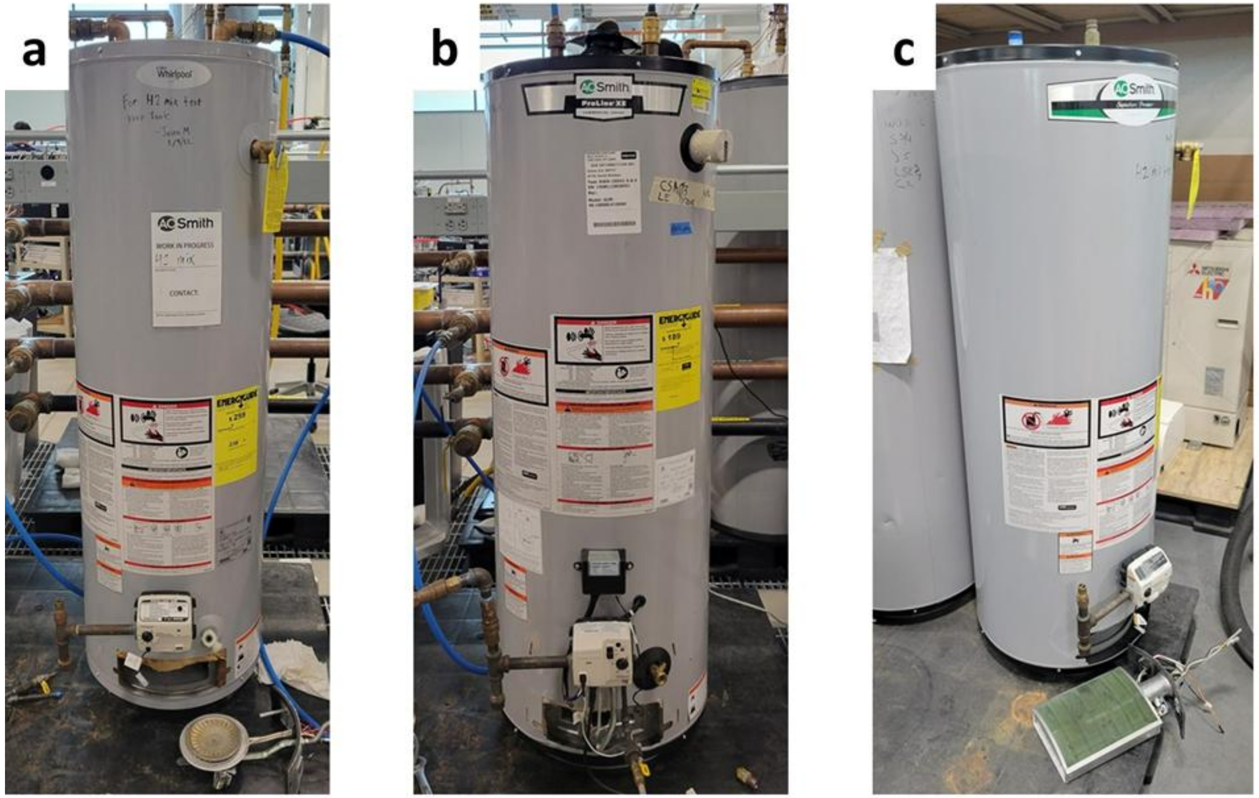
b) 40-gallon atmospheric unit with an ULN 40,000 Btu/hour burner and powered damper

c) 40-gallon atmospheric unit with an ULN 40,000 Btu/hour burner, no damper

Test the limits of hydrogen that can be added to NG for use as a fuel on these products

Tests based on CSA/ANSI Z21.10.1 standards

Pass/fail criteria will be initially based on properties such as combustion, flame shape/ laziness, noise propagation, and flashback.



Note: flammable vapor ignition resistance (FVIR) and lint, dust & oil (LDO) testing were not done (and need to be)

Test Results: Residential Partial Premix Units (Up to 30% H2)

Unit #	%H2	5.5.1 Carbon	5.5.2 Flash back	5.5.3 Smoke Test	5.5.4 Cold Test	5.5.5 Combustion Space	5.5.6 Wind	5.5.9 No Changes	5.5.11 Flame Lifting	Other
Unit (a) 30 gallon, 30 kBtuh, low NOx unit	10	Pass	Pass	Not Done[3]	Pass	Pass	Pass	Pass	Pass	No
	20		Pass[2]							Mild Noise
	30		Fail[1]							
Unit (b) 40 gallon, 40 kBtuh, ULN w. powered damper	10	Pass	Pass	Pass	Pass	Pass	Pass[4]	Pass	Pass	Noise
	20									
	30									
Unit (c) 40 gallon, 40 kBtuh, ULN, no damper	10	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Noise
	20									
	30									

Fail[1]: Heater (a) failed the flashback test when 30% hydrogen was introduced to the gas stream.

Pass[2]: At 20% hydrogen during the flashback test, a split-second flame was occasionally noticed at the orifice when shutting the unit off.

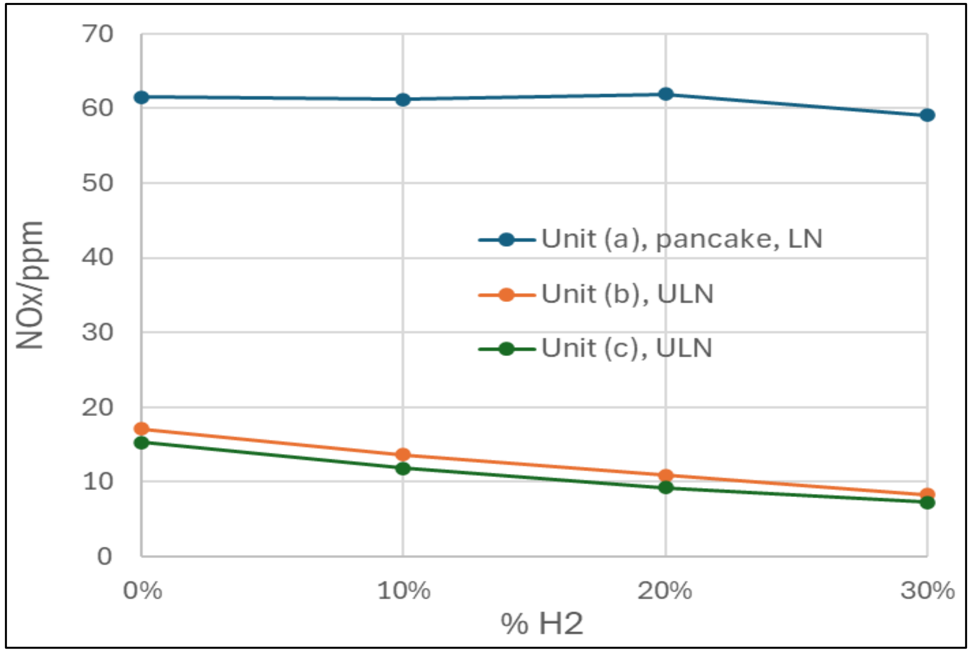
Not Done[3]: Smoke test was not run for unit (a) because the mixer face could not be safely accessed while the unit was running

Pass[4]: Unit (b) would intermittently give a "lint buildup" error and the flame would subsequently go out. May have been a thermal switch shutting the unit off due to hydrogen's higher flame temp.

AO Smith

NOx Emissions

	NOX (PPM) (AF)		
% H2	Unit (a) 30 gallon, 30 kBtuh, low NOx unit	Unit (b) 40 gallon, 40 kBtuh, ULN w. powered damper	Unit (c) 40 gallon, 40 kBtuh, ULN, no damper
0%	61.5	17.1	15.3
10%	61.2	13.6	11.8
20%	61.9	10.9	9.2
30%	59.1	8.3	7.3



- For the pancake, NOx emissions remained flat or slightly reduced
- For the ULN burners, a consistent decline in NOx was observed, reducing to about half, owing to the excess air dilution impacts
- These results are in line with other lab's findings

AO Smith

Internal Work on Fully Premix Commercial Units (Up to 30% H2)

<u>Commercial Fully Premix Products Tested</u>

d) 50-gallon high efficiency unit with a 76 kBtuh low NOx burner and powered vent

e) 199 kBtuh condensing ULN tankless unit

f) 53-gallon high efficiency side-fire unit with 70 kBtuh ULN burner

Test the limits of hydrogen that can be added to NG for use as a fuel on these products

Tests based on CSA/ANSI Z21.10.3 standards.

Pass/fail criteria will be initially based on properties such as combustion, flame shape/ laziness, noise propagation, and flashback.

In addition to some of the residential tests, the commercial tests also include a Back Pressure Test (Sections 5.6.7) and a Safe at Min Flow Test (Section 5.6.9)

Test Results: Commercial Fully Pre-Mix Units (Up to 30% H2)

Unit #	%H2	5.5.1 Carbon[2]	5.5.2 Flash back	5.5.3 Smoke Test[3]	5.5.4 Cold Test[4]	5.5.5 Combustion Space	5.5.6 Wind[5]	5.5.7 Back Pressure	5.5.9 Safe at Min Flow[6]
Unit (d) 50 gallon, high eff., 76 kBtuh, low NOx unit w. power vent	10 20 30	Pass	Pass	NA	Pass	Pass	Pass	Pass	NA
Unit (e) 199 kBtuh, ULN tankless condensing	10 20 30	NA	Pass	NA	NA	Pass	NA	Pass	Pass
Unit (f) 53 gallon, 70 kBtuh, ULN, side-fire condensing	10 20 30	NA	Pass	Pass	Pass	Pass	NA	Pass[1]	NA

Pass[1]: Flame went out twice during the first round of back pressure tests on unit (f) with indicated error suggesting insufficient gas supply, or too low of a supply voltage. Upon retesting, the unit performed without any problems. The error was likely the result of the European unit not being subject to ANSI/CSA test standards.

Carbon[2]: Unit (d) was the only one to receive the carbon check because it had a combustion chamber that was easily accessible

Smoke[3]: Test was only performed on unit (f) because the mixer face on the other units could not be accessed during heater operation.

Cold[4]: Test is for storage water heaters and thus does not apply to unit (e).

Wind[5]: Units (e) and (f) not subjected to wind test since combustion chambers completely enclosed.

Safe[6]: This test only applies to tankless unit (e).

Summary of In-House Testing

Residential Units (self-aspirating):

- Heater (a) passed with up to 20% hydrogen, failed flashback test at 30%.
- Heater (b) and (c) passed with up to 30% hydrogen.
- NOx emissions reduced by up to 50% for the ULN burners with higher hydrogen blends.
- Except for the pancake burner which sometimes flashed back with a 30% hydrogen mix, these results are similar to those of GTI Energy (Glanville, et al. 2022)*. GTI found no major issues or changes to the burner flames with hydrogen mix concentrations up to 30%.

Commercial Units (fully premix):

- Heaters (d) – (f) all passed with up to 30% hydrogen.

Summary:

- Residential units passed with up to 20% hydrogen, commercial units passed with up to 30% hydrogen.
- Further testing needed for higher hydrogen blends and specific units.

AO Smith

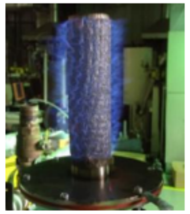
* *Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance*, Glanville et al., Energies, 2022

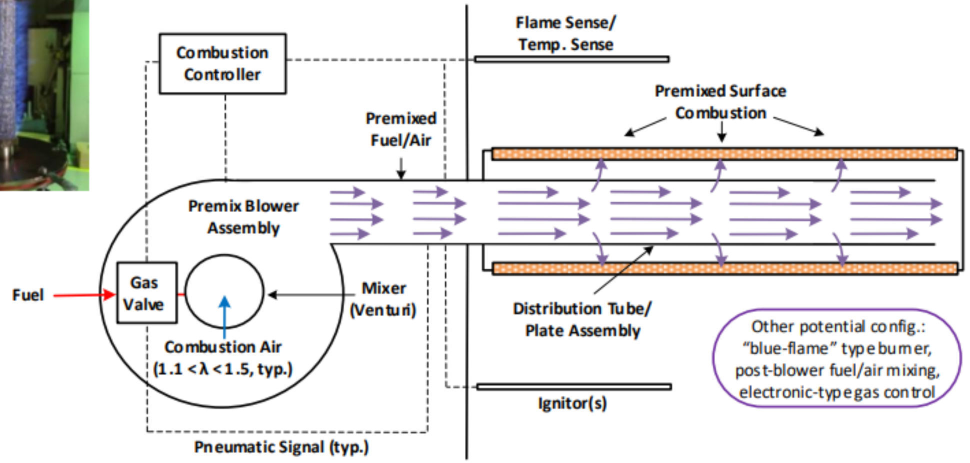
OEM Thoughts on H2/NG Mixtures and Some Needed Work

1. Gas valve supplier would need to evaluate their diaphragm material for long term use considering the hydrogen enriched environment
2. Thermal & pressure switches are tuned for regulatory shutdown that is temperature based using NG combustion (all atmospheric LDO) & functional venting based on pressures developed with NG combustion (all PV systems). Need to evaluate all those functional systems with each %H2 chosen to ensure effective operation.
3. Need to evaluate the long-term combustion byproduct environment to see if any combustion byproducts are corrosive enough to cause any problems at the burner surface, combustion chamber & baffle material. Also, depending on testing outcome of ANSI Z21.10.1, there are surface temps taken for burners, pilots, shields, etc. that may mandate the use of stainless, resulting in a cost increase.
4. For high altitude up to 10100 ft, the full range of operational characteristics are satisfied today. Some level of H2 mixing could propagate additional unit SKUs (altitude kits) to ensure the unit operates properly at each altitude marker, especially where pressure switches in PV/PDV blowers are used. Could also add field complexity & unintended confusion leading to potentially improperly functioning installs.
5. Finally, there is concern over the millions of units in the field that could potentially be a problem & certainly not cost effectively replaced. Pancake style burners particularly seem to be problematic.

AOS High Efficiency WH Products Certified for 20% H2 in EU

- The BFC-series of condensing, high efficiency, premix water heaters (28 to 120 kW) has been tested by EU testing agency for operation on G20 reference gas (methane) mixed with up to 20% hydrogen.
- Combustion tests and special tests like blocked flue etc. according to EN 89 were repeated for these gas mixtures without changing the appliance or the settings.
- Tests showed that there were no safety-relevant problems with this modified fuel gas composition; only the heat input (and the output) decreased by up to about 6%.
- **Conclusion:** If no further action is taken, the appliance will continue to operate safely when G20 is replaced with a mixture containing up to 20% H2.





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Hydrogen is “Industry Ready” in Europe

- Europe has developed ‘Tiers’ based on %H2:
  - Up to 20%: no modifications required to operate safely and meet performance
  - Up to 100%: full replacement of equipment is necessary to operate safely and meet performance requirements
  - Hydrogen Ready: leaves factory ready for up to 20% H2 but can be converted to 100% operation in <8 hours by exchanging a few components in the gas train
- Most burner companies have developed burners certified for G222 (23% H2); many have developed 100% H2 burners
- Several EU OEM’s have developed prototype boilers that run on 100% H2 that are currently undergoing trials
- AOS did some testing with 100% H2 on a 60kW commercial water heater using a perforated 'can’ burner. Tests were characterized by:
  - heavy oscillation, unstable burning with low frequency pulsations (audible sound)
  - High pressure drop limited maximum input to 35 kW
  - Condensate issues in the fire tube (higher dew point)

Summary: Self-Aspirating Burners

- Self-aspirating burners have operating characteristics that can be sensitive to the geometry, operating conditions and gas properties.
  - Can be designed to operate with any fuel mixture, but if the properties suddenly change, these burners may be more susceptible to flashback, flame lift and other instabilities
  - Partial pre-mix (pancake) more so than full premix (ULN)
- There have been several excellent studies carried out on self-aspirating burners with H2/NG mixtures:
  - Consensus seems to indicate that these types of burners will operate safely up to 20% H2
  - Data in this study agree with this consensus up to 20% H2
- Some OEM concerns remain, but for *new equipment*, should not become an issue as long as there is no proliferation of SKU's.
- Main concern remains the millions of legacy products in the field that could potentially be problematic & certainly not cost effectively replaced.
  - Pancake style burners could especially prove problematic.
  - If there is an issue, who is responsible?

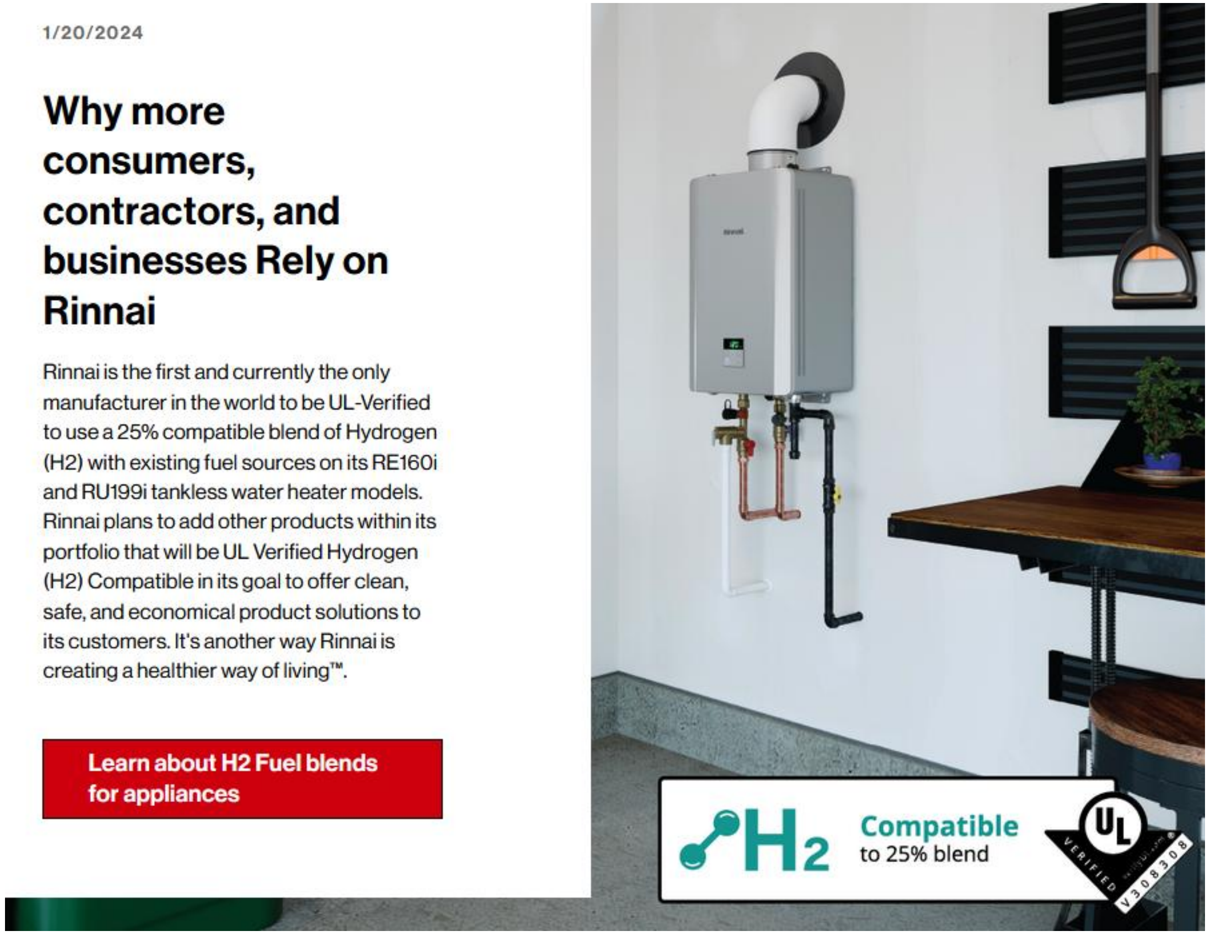
Big Picture – Codes and Standards

Consensus/industry standards organizations need research to make informed technical decisions:

- CSA Z21/83 issued formal interpretation that **equipment certified with "Test Gas A"** are suitable to operate with a 5% H_2 blend in 2023 (allowing trials to proceed)
- CSA Z21/83 H_2 groups are establishing pathways for **new product certification** – to new Test Gas B (tent. 20% H_2 blend) or Test Gas I (100% H_2)
- UL 795 now provides path for **boilers** to certify with a 25% H_2 blend, UL provides custom pathway for all other equipment too (right)

But what about **existing equipment** operating > 5% H_2 blends – should they all be replaced?

Working with UL – Rinnai achieves "first" certification with H_2 Blends in North America (up to 25%)



Source: Fulton, Rinnai

Big Picture – Preliminary CA TEA

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

Big Picture – Preliminary CA TEA

Blending "Tiers" by Volume:

- **Lower** blend ratios:

Do not require any modifications to adopt H_2-blended natural gas and operate safely and meet performance requirements

- **Mid-to-High** blend ratios:

Require minor equipment and/or controls modifications to permit adopting H_2-blended natural gas mixtures

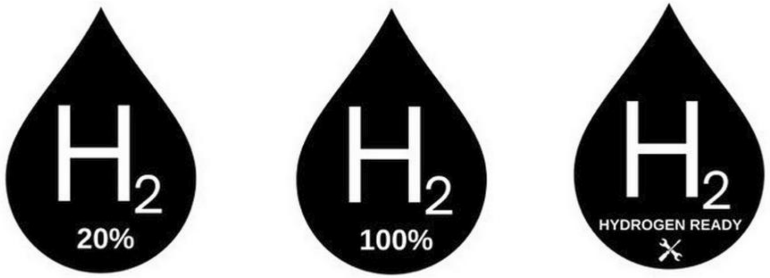
Typically implemented in-situ and with minimal resources (e.g. re-commissioning within an 8-hour period), to continue to meet performance requirements and operate safely.

- **Higher** blend ratios:

Up to 100%* H_2 where full replacement of equipment is necessary to operate safely and meet performance requirements.

Hydrogen Home, Gateshead

Components changed in conversion



Source: Bosch, Heating & Hotwater Industry Council (UK)

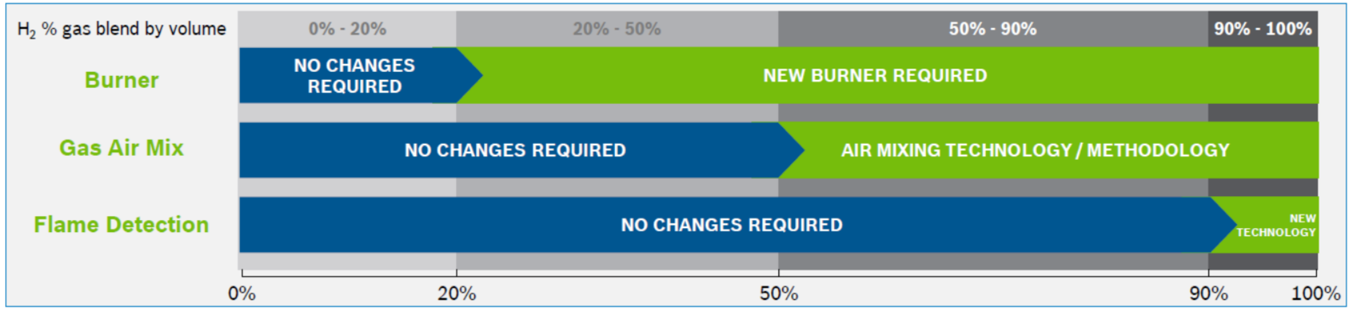
Hydrogen-ready boilers developed for UK H_2 distribution demos can be converted in-situ from accepting lower blends to 100% H_2, with certification and labeling schemes catching up

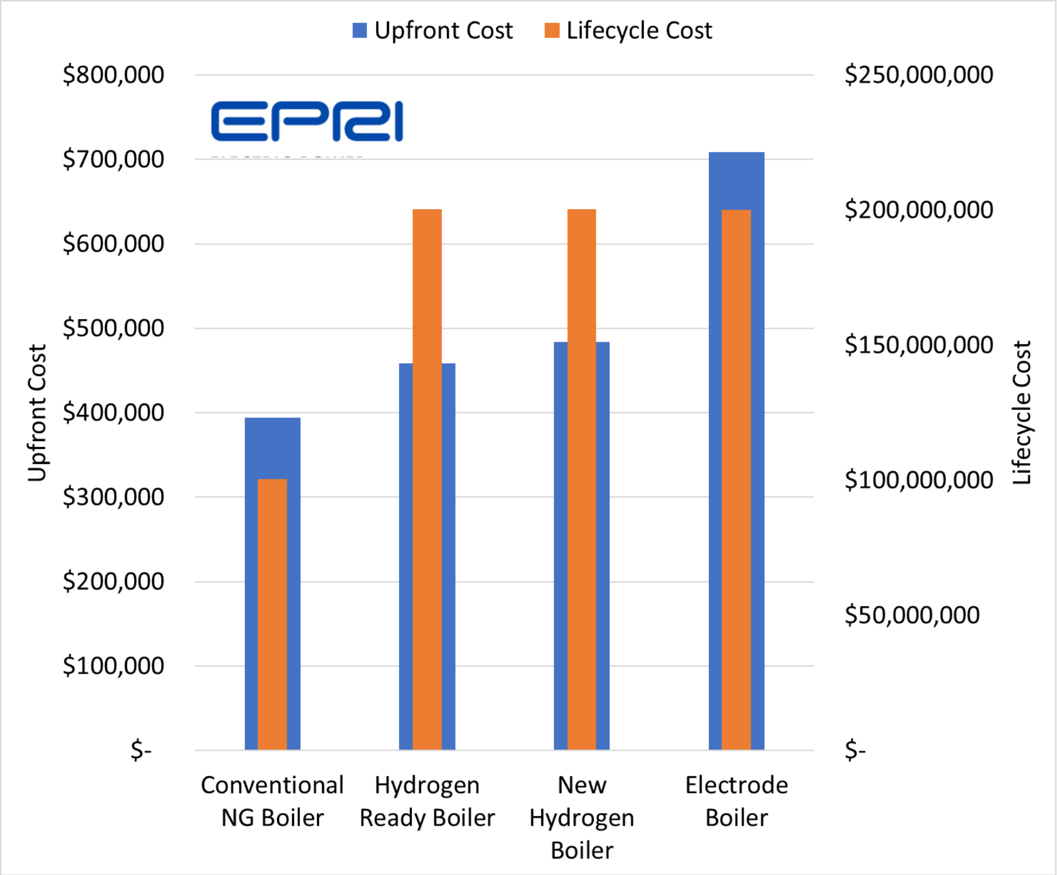
*Where "100% H_2" is mentioned, this may include mixtures of as low as 95% H_2 wherein mixtures of 95%-100% H_2 are considered within scope of NFPA 2 and similar hydrogen technology codes & standards.

Big Picture – Preliminary CA TEA

<u>TEA: On Costs & Benefits</u> - For H_2 ready/100% H_2 equipment, *equipment* costs are limited but so is data

- Similar & maximum statewide GHG reductions from *MAEE + H_2* and *Partial Electrification + H_2*
- Increasing evidence that for **H_2 < 30%, no cost/retrofit needed**, certifications in US/Canada already active
- UK/EU OEMs have noted H_2-ready and 100% H_2 equip. will have comparable costs at scale to natural gas equipment. In near term, **15%-20% premium is used**.
  - Key components: controls, burner, ignition/flame supervision; "cross over" points differ by type/vendor



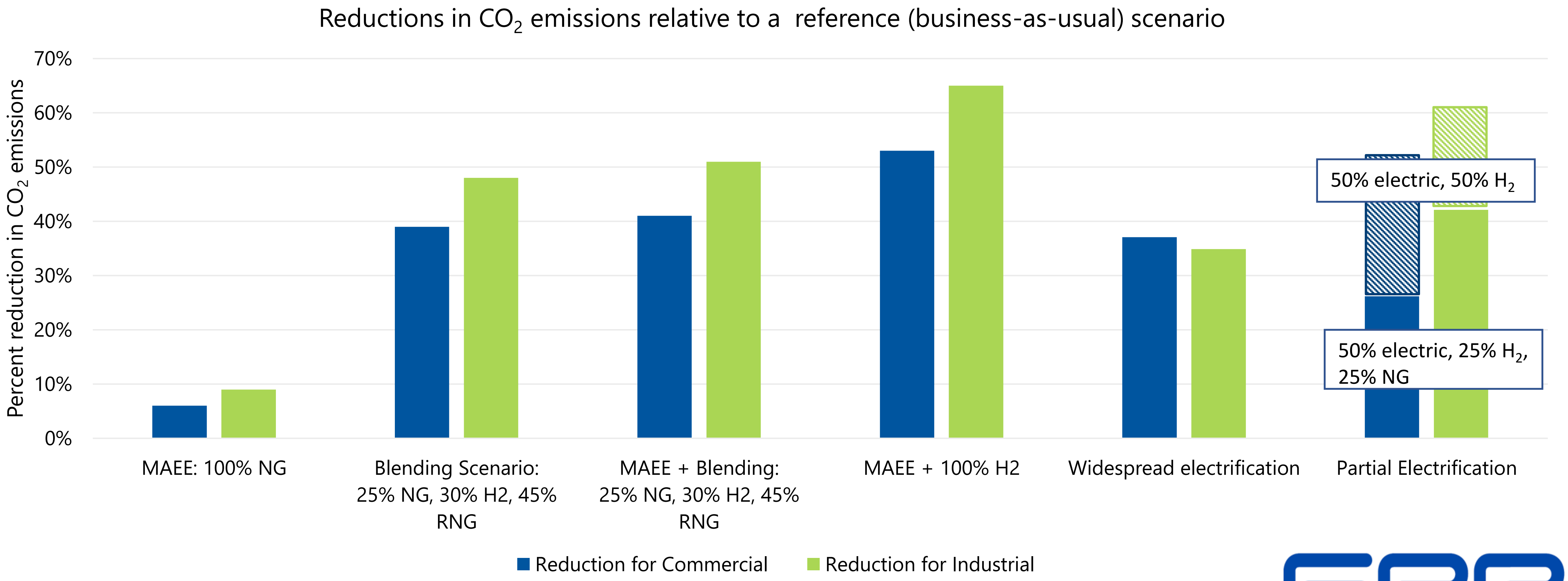


1) Boiler capacity of 15 MW and annual operating hours of 8000 are assumed
2) Lifecycle costs of Electrode boiler includes cost reductions due to monetized non- energy benefits

Prelim. TEA Summarized in 2023 ACEEE Conference Proceedings: <u>link</u>

Big Picture – Preliminary CA TEA

Draft/Preliminary Results: Subject to Change



- H_2 blending significantly reduces CO_2 emissions
- 100% H_2 maximizes the reduction in emissions (assumed H_2 cost 2X NG, up to 0.3 MMT H_2)
- Partial Electrification provides comparable reductions in CO_2 emissions as using 100% H_2

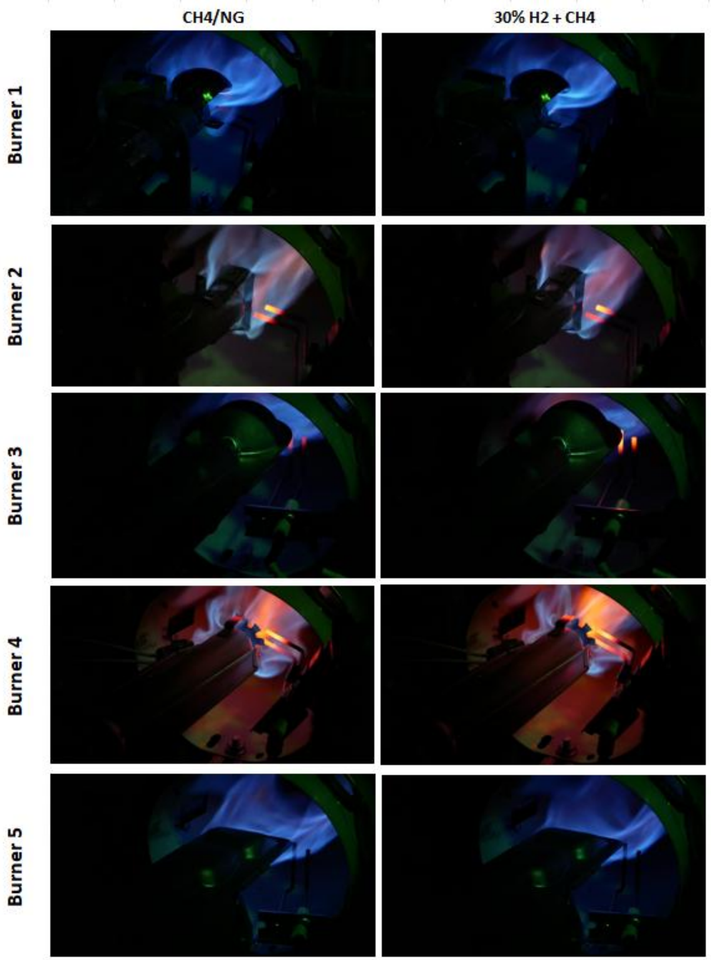
ELECTRIC POWER RESEARCH INSTITUTE

Big Picture – What have we learned from other studies?

Equipment Tested or Under Test (one or more):

- **Heating Equipment:** Central warm-air furnaces (non-weatherized), commercial furnaces (weatherized), wall furnaces, boilers (hot water), water heaters (storage & tankless-type) direct vent & unvented space heaters, gas-fired heat pumps (sorption-type)
- **Residential Appliances & Cooking:** Dryers, hearth products & fireplaces (incl. patio), range/ovens, outdoor grills, decorative lighting,
- **Commercial Cooking:** Commercial ranges, charbroilers, fryers, convection, pizza, & deck ovens, standing pilots, griddles

Most testing performed is to research *impacts on existing utility customers,* testing typ. up to (or exceeding) 30% H_2 blended – understood to be an 'up to' near term value for North American utility blending, and a nominal value transitioning within NFPA 70 from Group D to Group C hazard classification



Five Dryer Burner Tests in '23

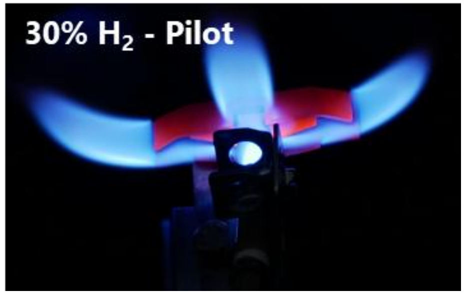
Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

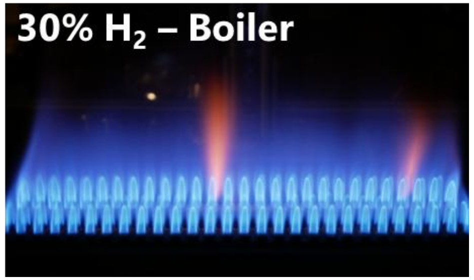
Big Picture – What have we learned from other studies?

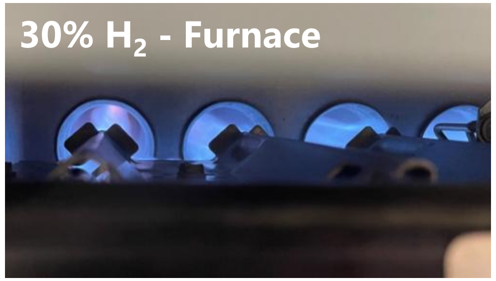
2024 Meta-Study

Themes from 80+ *heating equipment* tested: In unadjusted customer equip., will blended H_2/NG…

- 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? **Not likely**
- **Increase leakage within facility?** **Not worsened by blending**







- 2024 Meta-study pub. '24 focused on data trends
  - Drew from 30+ studies with published testing data/results
  - Focused on impacts on flame stability, heating capacity, emissions (NOx/CO), leakage enhancement & CH_4/H_2 slip

*Glanville, P., Fridlyand, A., Zhao, Y., Kar, T., Asher, W., Jogineedi, R., (2024) *Is the Heating Industry Hydrogen-Ready? – A Meta-Analysis of Hydrogen Impact Assessments on Combustion Equipment in Buildings* , Proceedings of the 2024 ASHRAE Winter Conference.

Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

Blending H_2 into the Gas Grid – Leakage

Are significant/costly retrofits are needed to operate safely?

Recent evidence suggests that for typical operating pressures (<10 psi), there is **no leakage enhancement** of H_2 versus natural gas, however **more data needed**

Static Leakage from Low-Pressure Dist./Equip.

- While H_2 is *only* 24% smaller than CH_4, it may preferentially leak/slip, limited data
  - 8X lower MW, 3.6X diffusivity and 20% lower visc. (STP)
- Two distinct modes: 1) Convection due to ΔP and 2) Diffusion/permeation due to ΔC*.
  - Assumptions for higher P pipelines do not apply
  - Cannot use std. equations (Darcy-Weisbach / Fick's Law), which suggest 2.8-3.0X leakage enhancement
  - Small gaps, low Re, issue with continuum approx. & no slip assum., leak paths with Kn <<1 and not constant

In UK Hy4Heat project** (above), team used a boiler room, to gradually test (at 0.3 psig) with air, CH_4, then H_2, determining "*data collected indicates that a leak tight system in methane is also leak tight in hydrogen*". With field component assemblies and 40% H2 blends, the EU THyGA project*** reached similar conclusions.

*Excellent review by Mejia: https://www.sciencedirect.com/science/article/abs/pii/S0360319919347275 // **Source – THyGA Project: https://thyga-project.eu/d3-7-tightness-testing-of-gas-distribution-components-in-40h260ch4/
***Source – Hy4Heat Project: https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e5624fa6935c655a14789a/1625645665898/Exp+test+commercial+pipework+FINAL.pdf

Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

Blending H_2 into the Gas Grid – Leakage

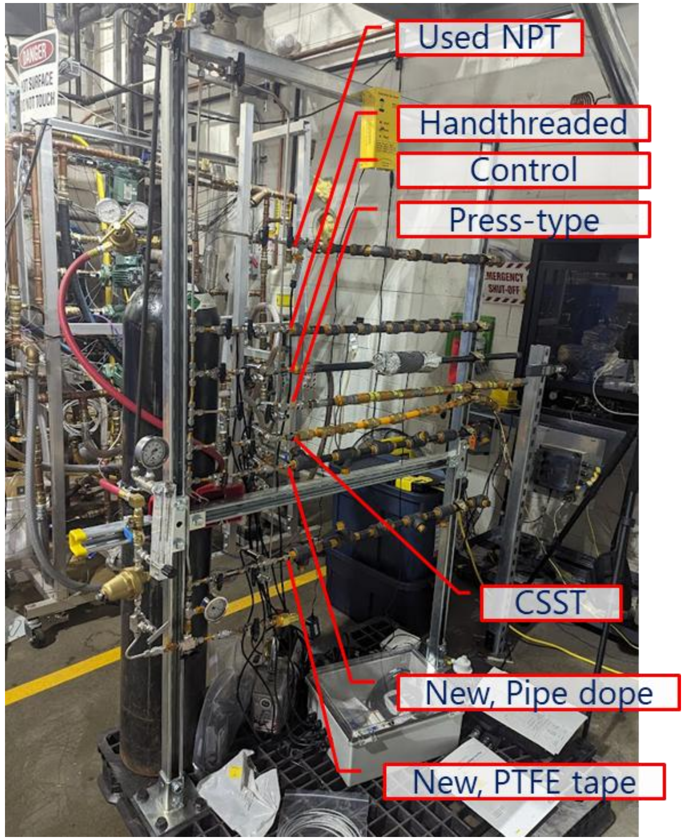
<u>Are significant/costly retrofits are needed to operate safely?</u>

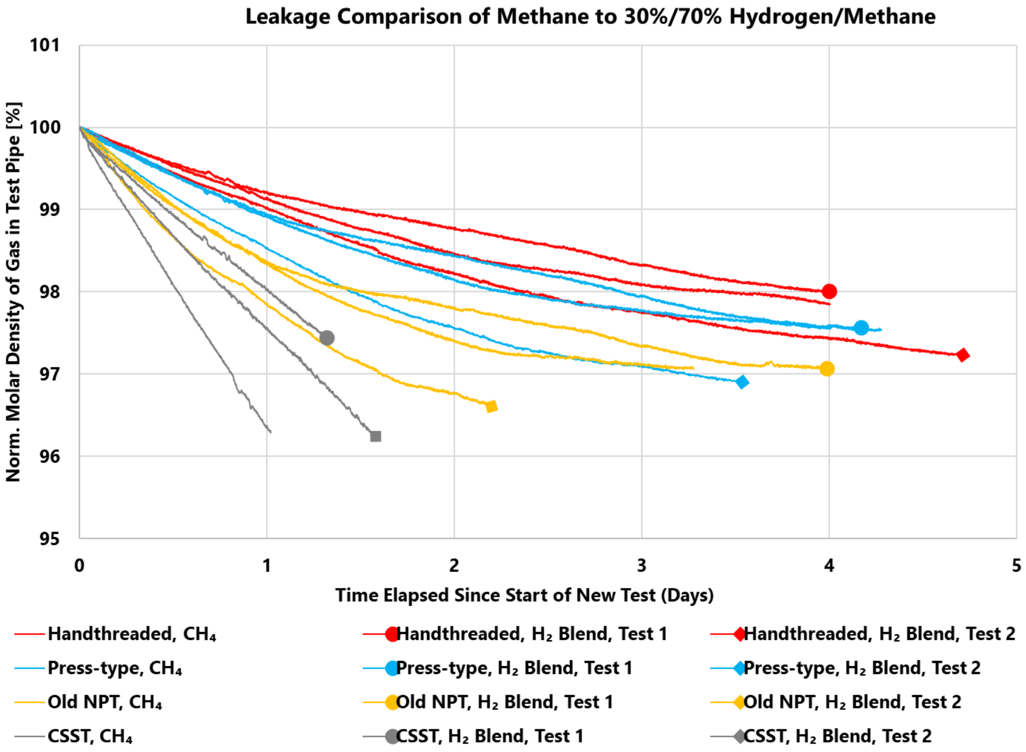
Limited U.S. studies on equipment/distribution with < 10 psig **do not show leakage enhancement**

CSA* tested components & manifolds (below), no sig. difference. Also pipe segments @ 5/20 psi, Steel, Copper, CSST piping/connections passed up to 15% H_2

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

GTI*** examined common piping indoor gas connections (right), made by engineers and plumbing technicians alike. Recent results agree that, under static conditions up to 30% H_2 will leak **at the same rate** as gas, in agreement with similar studies.





*Data Source - CSA: https://www.csagroup.org/article/research/appliance-and-equipment-performance-with-hydrogen-enriched-natural-gases;
** Data Source - UC Irvine https://www.sciencedirect.com/science/article/abs/pii/S0360319919347275
***Data Source: Forthcoming 2025 paper –Fridlyand, Aleksandr; Bushell, Mason; Zhao, Yan; Komar, Jess; Glanville, Paul. Hydrogen Integration in Buildings: Investigating Leakage from Common Gas Connections, [Future] Proceedings of the 2025 ASHRAE Winter Conference

Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

Blending H_2 into the Gas Grid – Facility

<u>Are significant/costly retrofits are needed to operate safely?</u>

Challenges with hazardous area classification:

- Many facilities classified for **Group D** hazardous gases in atmosphere (natural gas, propane, etc.)
- Based on ignition risk from circuits, motors, etc. (via *Max Experimental Safe Gap*) hydrogen (**Group B**) may shift hazard classification depending blending level

TABLE III
GROUP CLASSIFICATION CRITERIA

NEC Gas Grouping			IEC Gas Grouping		
Group	MESG (mm)	MIC ratio	Group	MESG (mm)	MIC Ratio
A	Acetylene		IIC	≤0.50	≤0.45
B	≤0.45	≤0.40			
C	>0.45 ≤0.75	>0.40 ≤0.80	IIB	>0.50 ≤0.90	>0.45 ≤0.80
D	>0.75	>0.80	IIA	>0.90	>0.80

Source: Bozek, Allan & Rowe, V.. (2010). Flammable Mixture Analysis for Hazardous Area Classification. Industry Applications, IEEE Transactions on. 46. 1827 - 1835. 10.1109/TIA.2010.2059591.

GTI Energy has employed ventilated enclosures to mitigate these risks for experiments

Disclaimer: Conclusions based on results and methods of studies referenced noted only and may not be widely applicable

Conclusions and What's Ahead

- An increasing array of heating equipment and components are designed for hydrogen, as blends and 100% H_2, in-situ conversion is feasible
- For existing equipment designed/certified for NG operating with hydrogen blends emerging experimental evidence suggest **in general**:
  - NOx & CO emissions will *decrease or remain flat*
  - Capacity will decrease within *5%-10% of Wobbe Index*
  - Equipment upper stability limits likely *well exceed fuel blending*
  - *No observed leakage enhancement* for equipment/distribution at typ. operating pressures
- Goal in research program is to build *body of evidence* concerning impacts, and:
  - Aggregate impacts of benefits/issues (e.g. air quality) vs. alternative scenarios (e.g. electrification)
  - Modernize interchangeability tools* & indices, informing remain-in-place determinations
  - Validate efficacy of equipment retrofits, in-situ mitigations, and inspection/O&M protocols

*Fridlyand, A; Zhao, Y; Asher, W; Glanville, P, *Burner Design Considerations for Hydrogen-blended Gas Operation,* ASHRAE Conference Proceedings 2023

Questions & Answers

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