The Future of Combustion in a Low Carbon World

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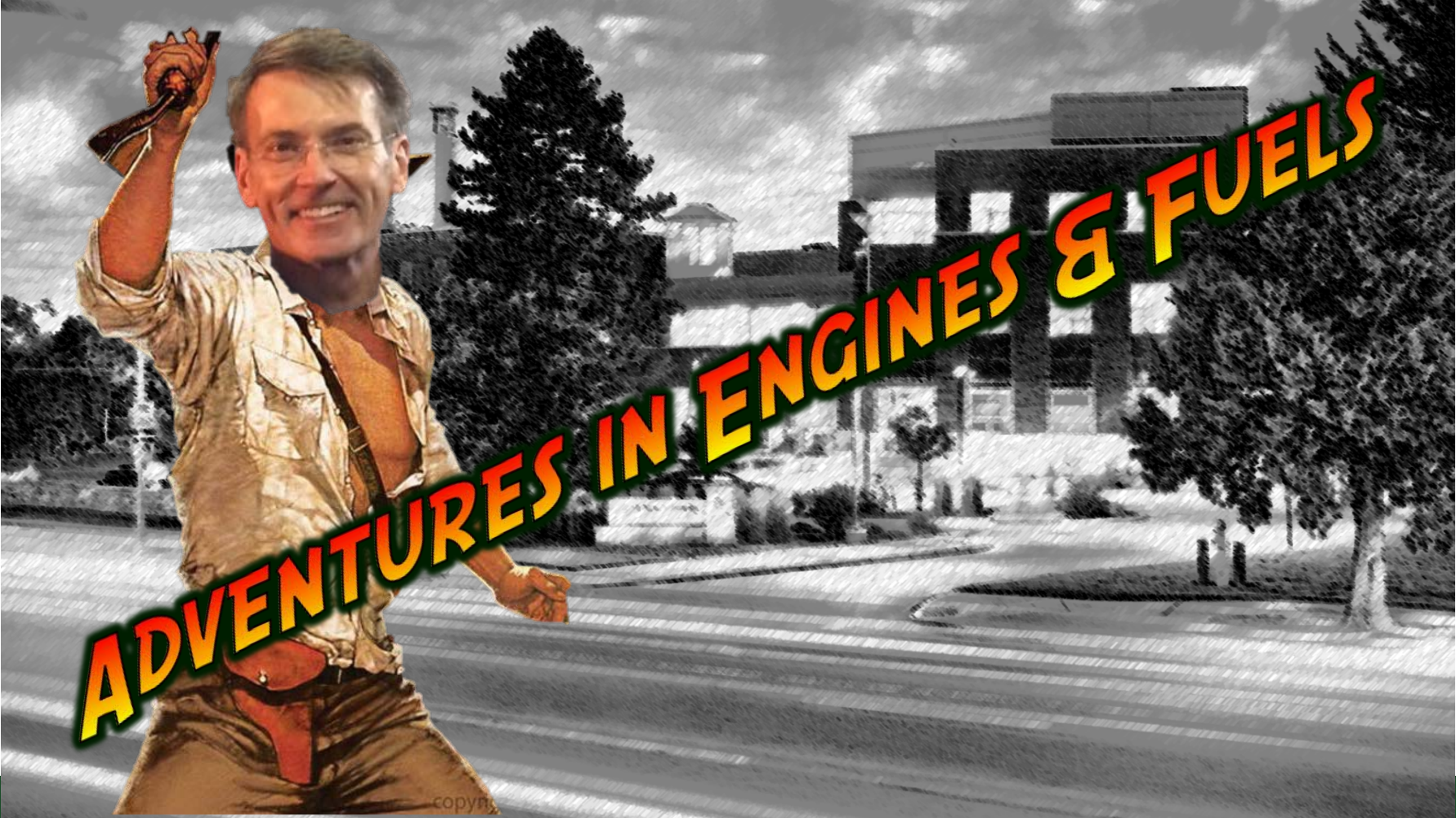
ASME Internal Combustion Engines Fall Conference

Nov 4, 2020

ENERGY INSTITUTE COLORADO STATE UNIVERSITY


ADVENTURES IN ENGINES & FUELS

Outline

- **Engines & Energy Conversion Lab**
- Biomass
- Alcohols
- Natural gas
- Algae-based biofuels
- Hydrogen

Early CSU Engine Lab, ≈1940

Fort Collins Power Plant (1935-1972)

Power Plant Interior (1992)

Early Days: No heat, toilets or windows!

CSU Powerhouse Energy Campus (2014)

Powerhouse: A Testbed for Building Systems and Social Innovation


https://vimeo.com/442580476/adbf7b7359

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Options for Sustainable Fuels

Biofuels

Sugars

- C4 sugars: corn, sugar cane, sorghum
- C3 sugars: barley,, rice, tomatoes, wheat, sugar beet
- Cellulose through additional process
- Typically used to produce ethanol

Gasification

- Produces syngas H_2 + CO
- Can make alkane fuels from Fisher-Tropsch process

Oils

- Soy, canola, sunflower, safflower, hemp
- Animal products
- Algae – lipids, carbohydrates, methane, H_2
- Typically used to produce FAME (fatty acid methyl esters)

Solar Fuels

Hydrogen – from electrolysis

Ammonia - from Haber-Bosch

Methane –

- Anaerobic digestion
- From H_2 + CO_2
- Engines or solid oxide fuel cells
- Can convert to methanol or DME (dimethyl ether)

Longer alkanes

- From H_2 + CO through Fisher-Tropsch

Four-Stroke “Humphrey Pump” – Liquid Piston Engine

- Atkinson full expansion cycle
- Tolerant of corrosive or tar-laden gases
- Well-suited to operation on biogas or producer gas
- Hypothesized application was water pumping in developing nations
- Large-bore, low-turbulence, cold combustion chamber

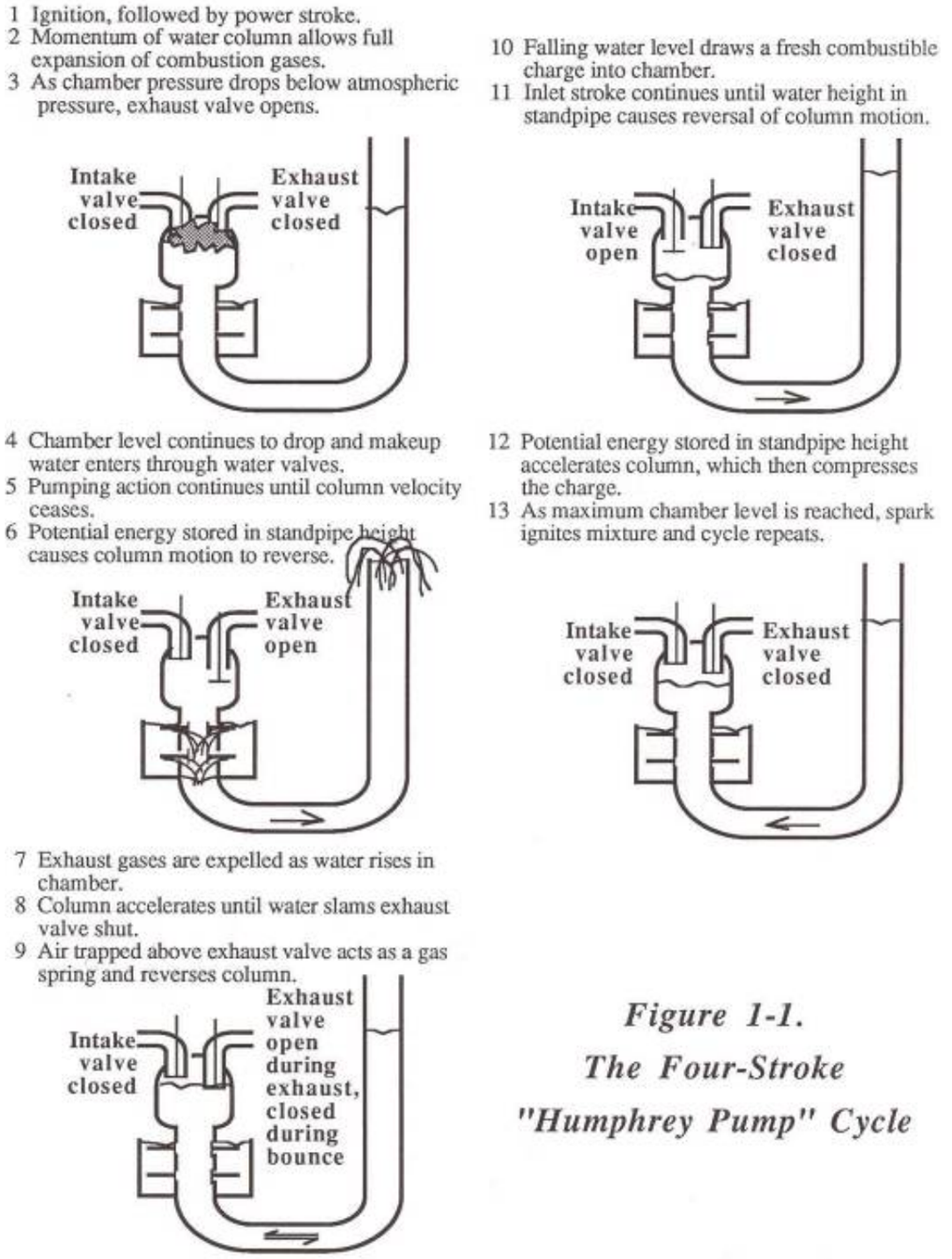
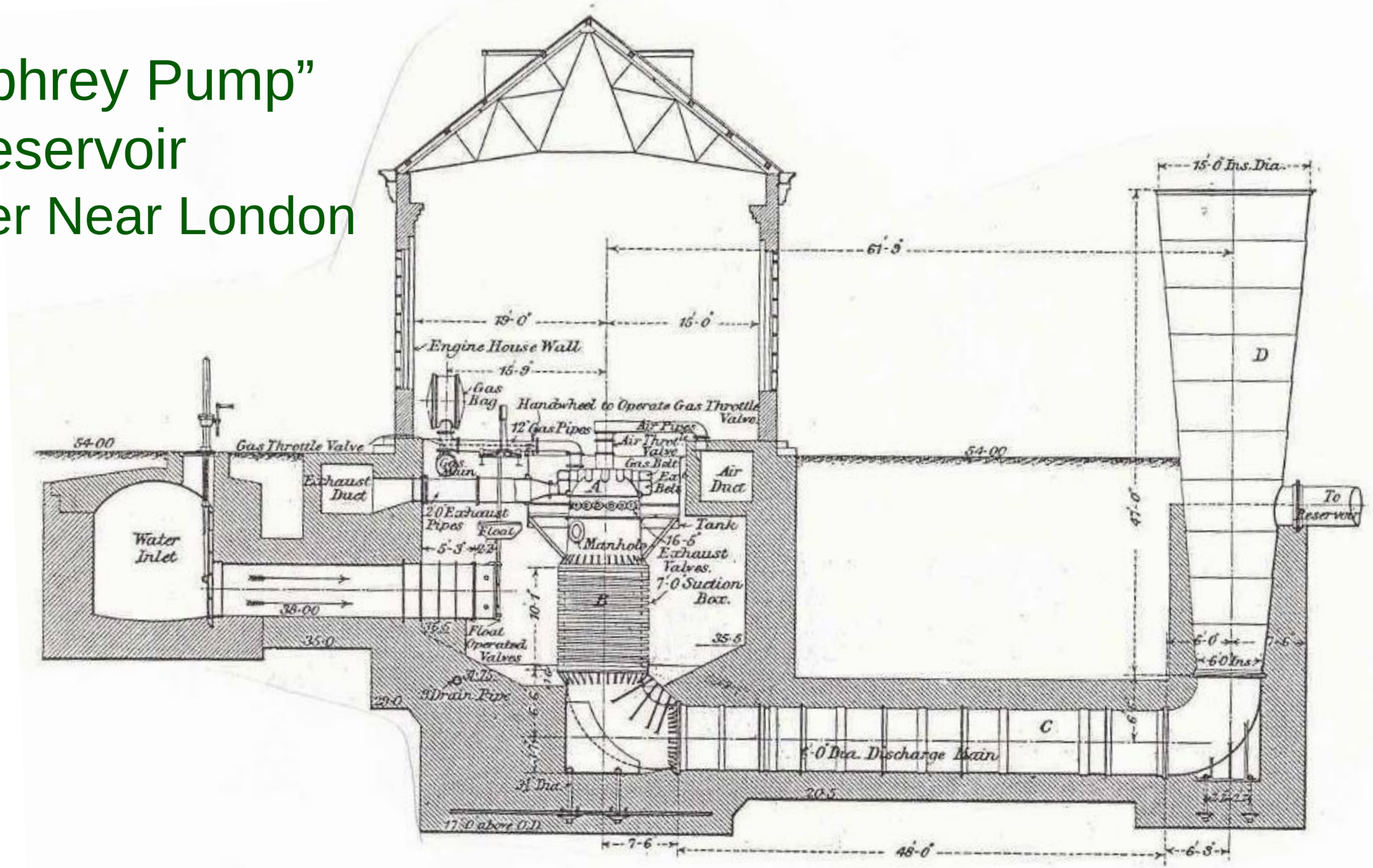
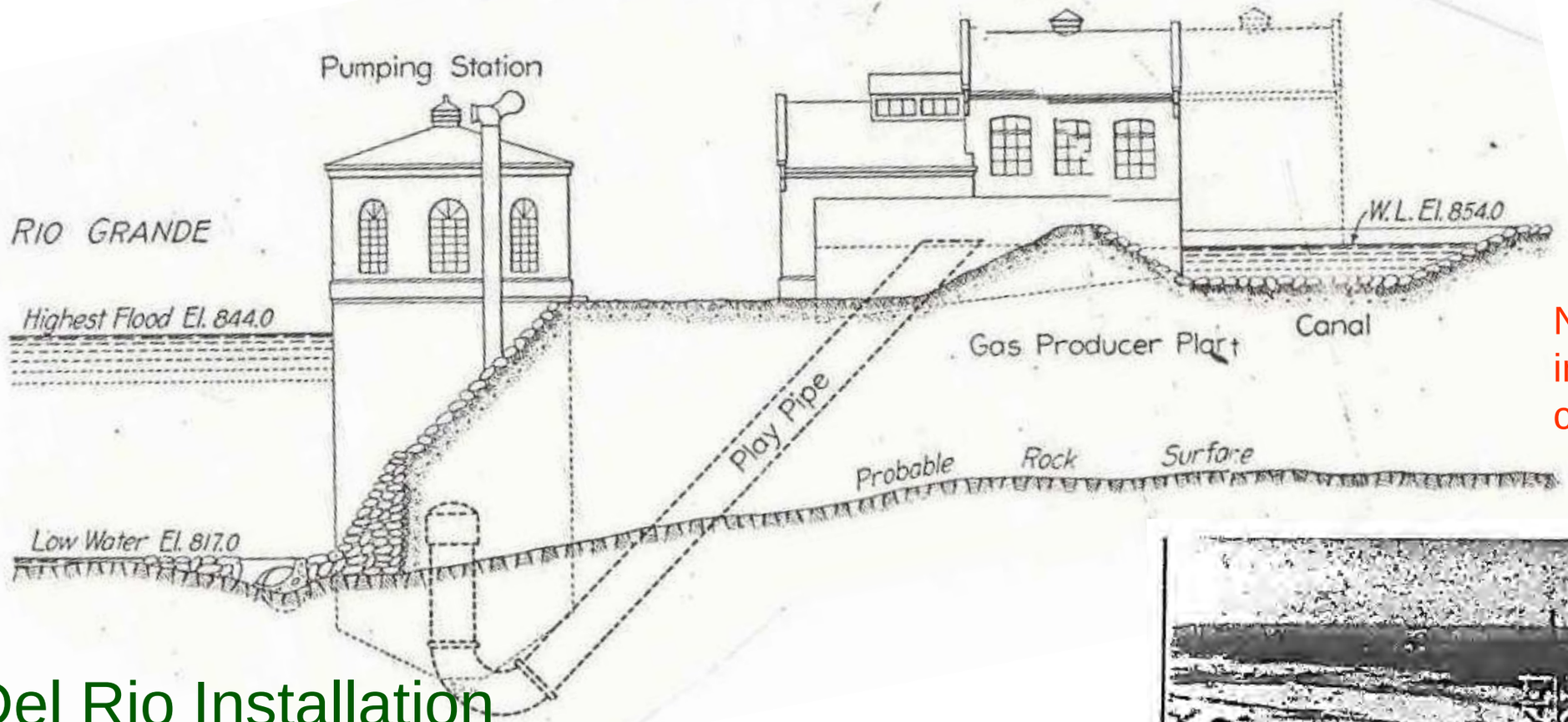


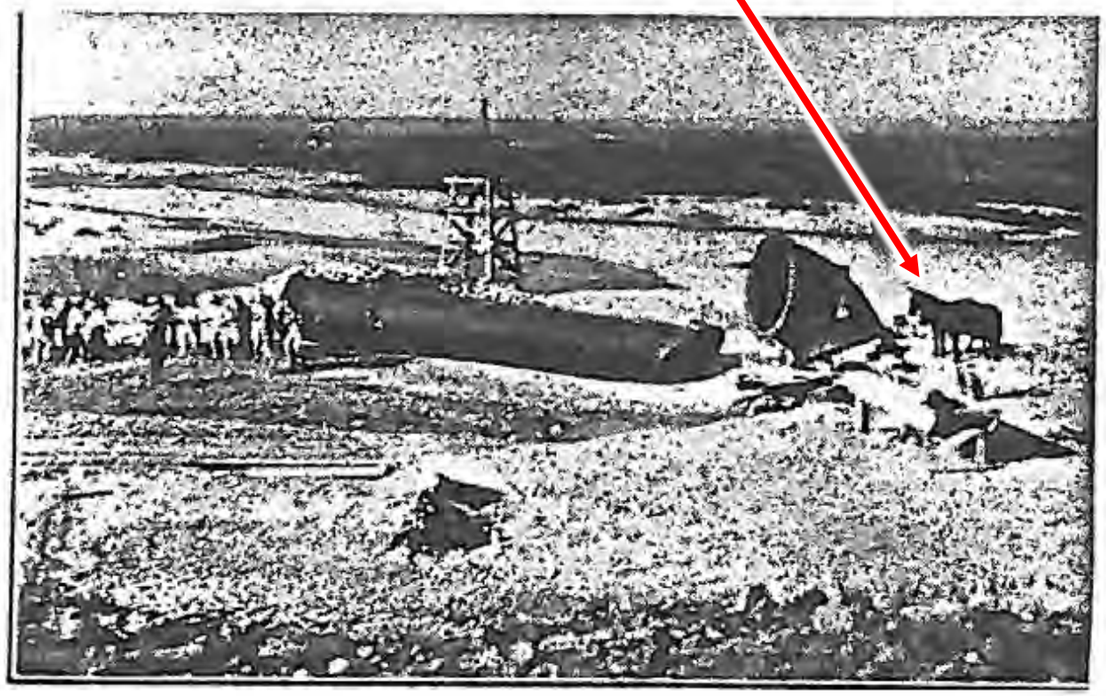
Figure 1-1. The Four-Stroke "Humphrey Pump" Cycle

4-Stroke “Humphrey Pump” at Chingford Reservoir On Thames River Near London





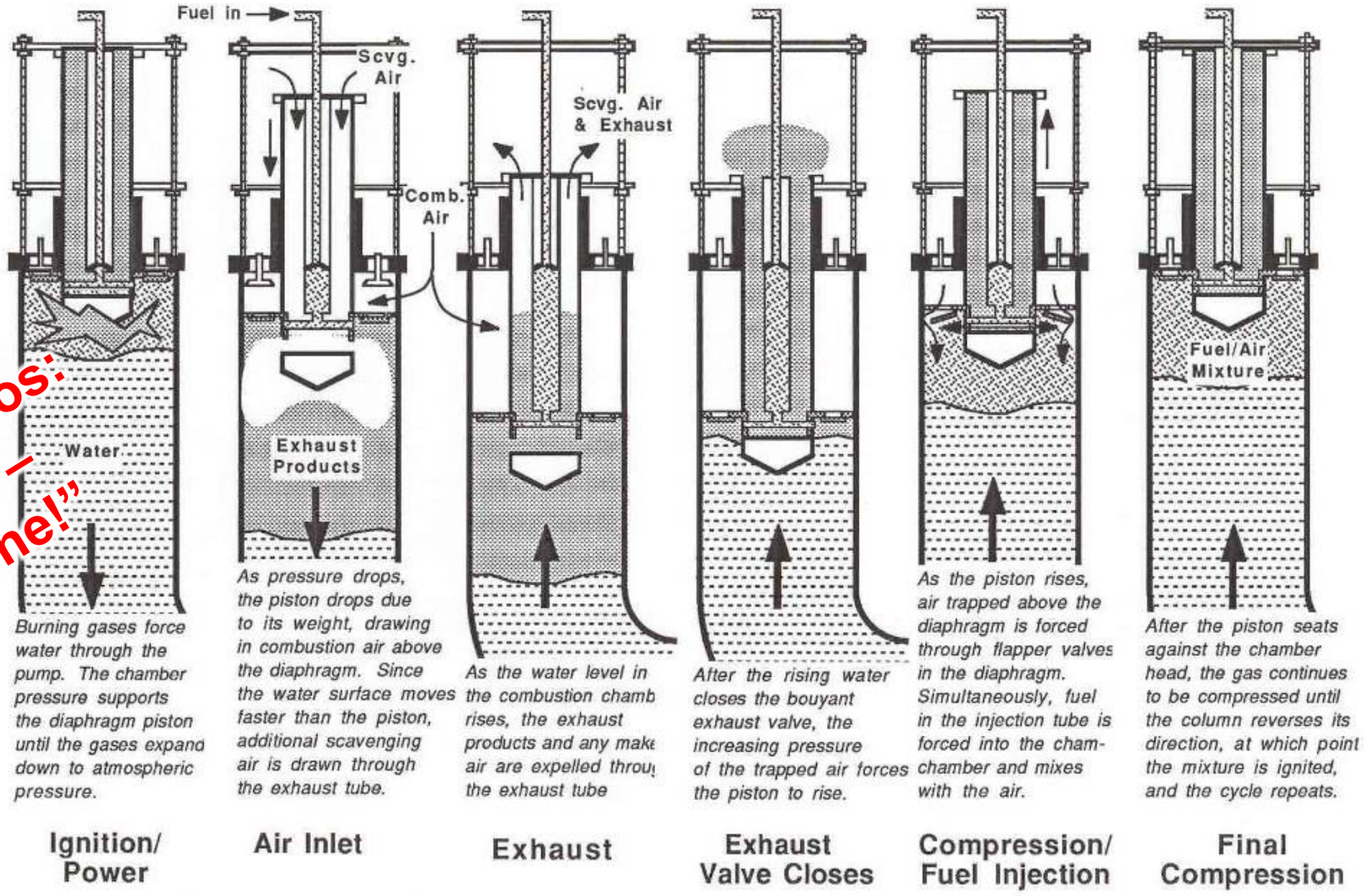
Note that a mule would fit in the combustion chamber



Del Rio Installation

- 1 of 2 in the U.S.
- 7 ft piston bore
- Operates on gasified mesquite wood
- Irrigates 10 miles^2 of land from the Rio Grande river

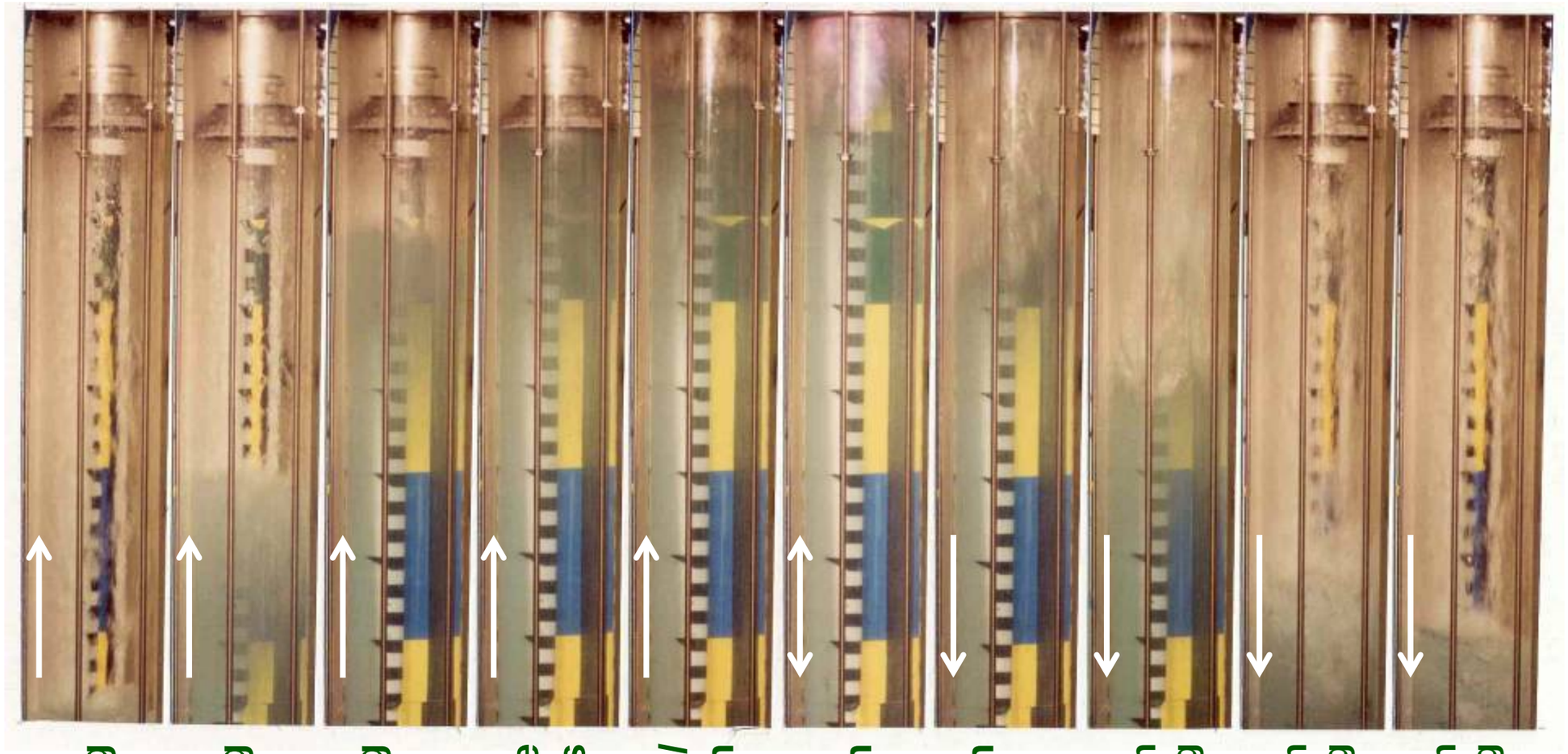
Direct-Injection 2-Stroke Liquid Piston Engine



Powerhouse Ethos:
"That's cool – Let's buid one!"

Liquid Piston Engine Lab at University of Texas, Austin

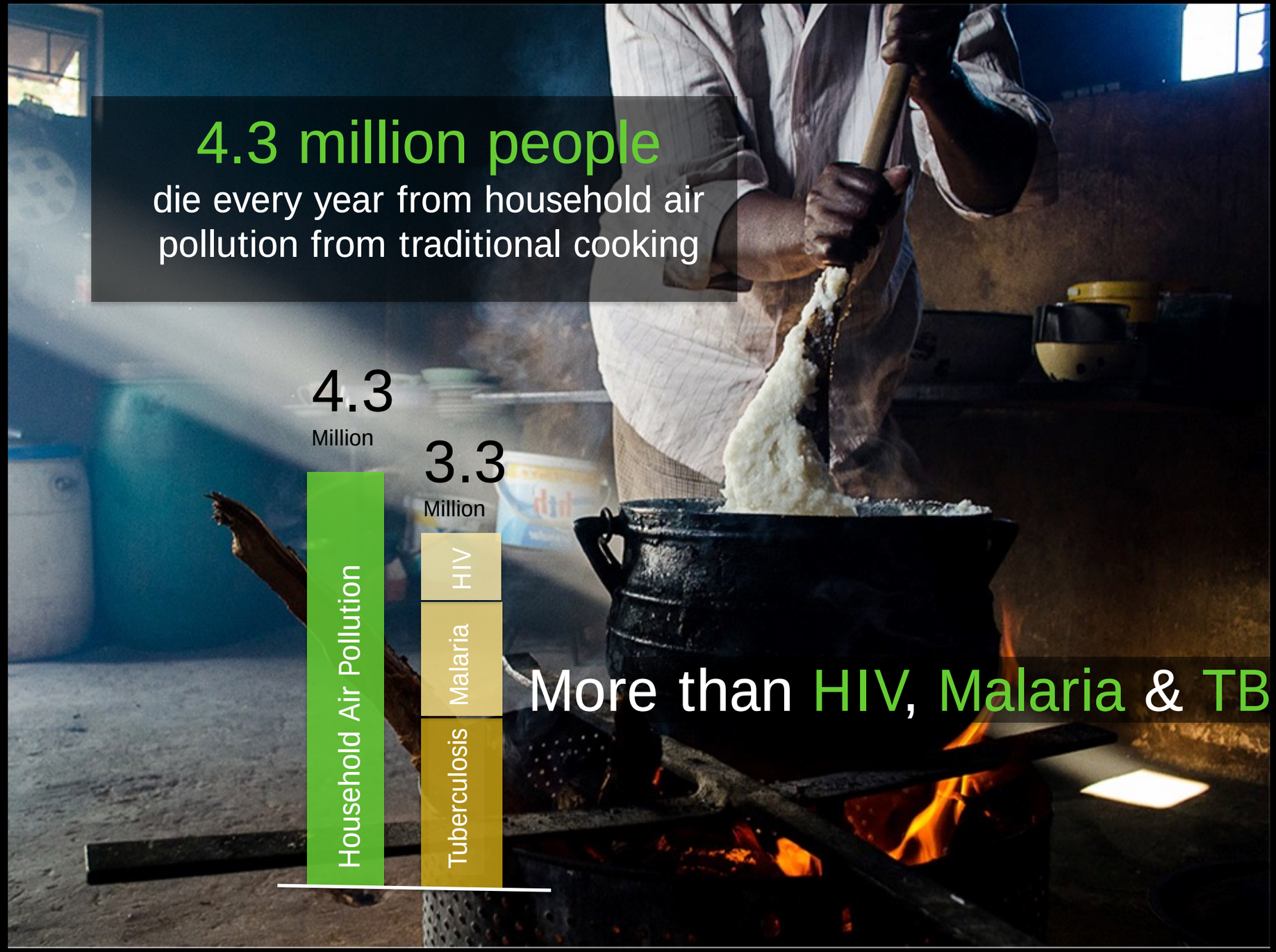
Direct-Injection Engine in Operation



Liquid Piston Engine as Borehole Pump

Also Prevents Acceleration Instability of Water Surface


Nearly 3 billion people use polluting, inefficient stoves or open flames to cook their food
GLOBAL ALLIANCE FOR CLEAN COOKSTOVES


4.3 million people
die every year from household air pollution from traditional cooking
4.3
Million
3.3
Million
Household Air Pollution
HIV
Malaria
Tuberculosis
More than HIV, Malaria & TB combined

Advanced Cookstove Lab, 2005

“Improved” Cookstove

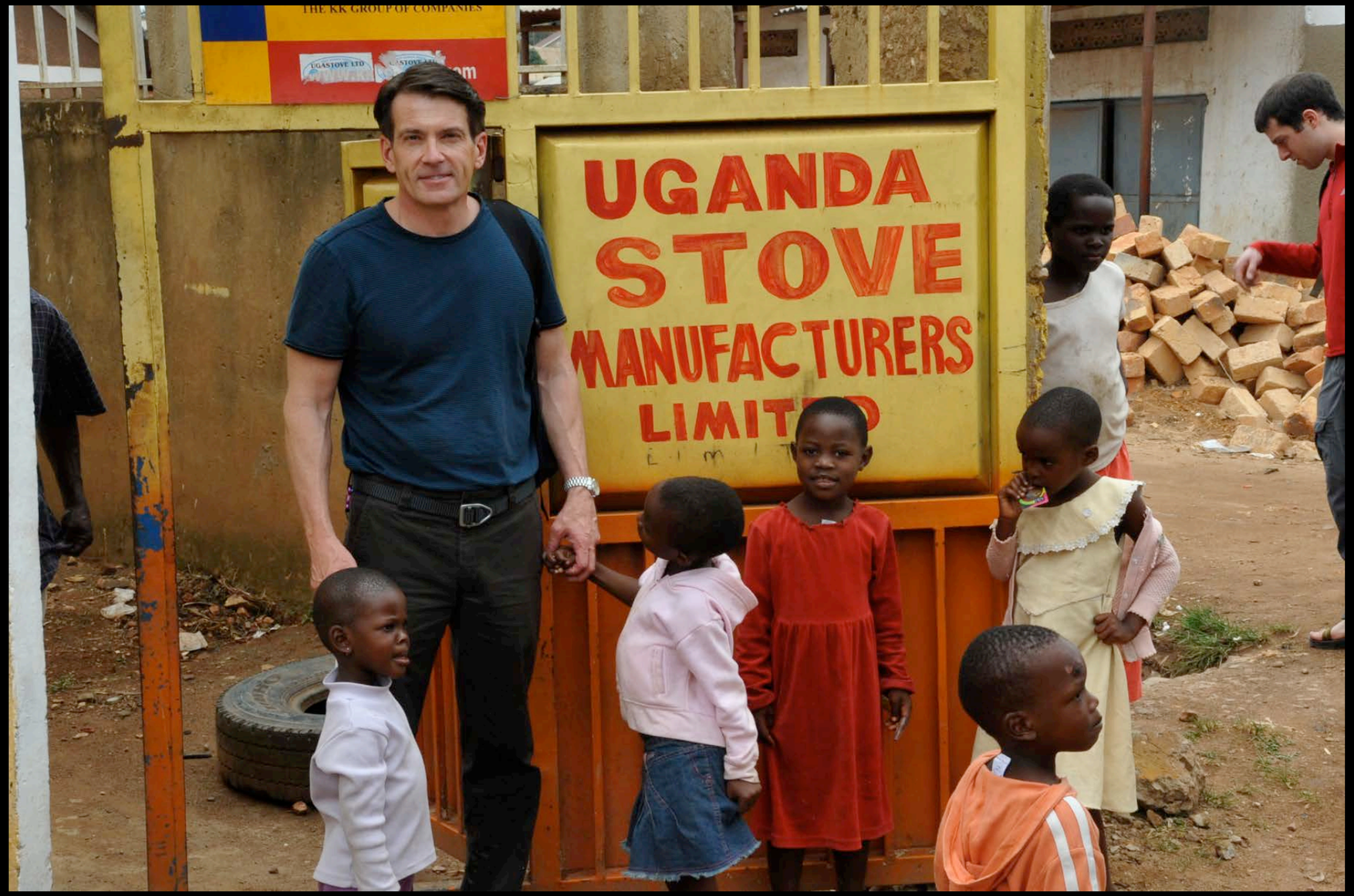
Photos: B. Willson, Uganda, March ‘09

Locally Built Stoves

Abuja, Nigeria – (Nov, ’07)

Photos: B. Willson, Nigeria – ‘09

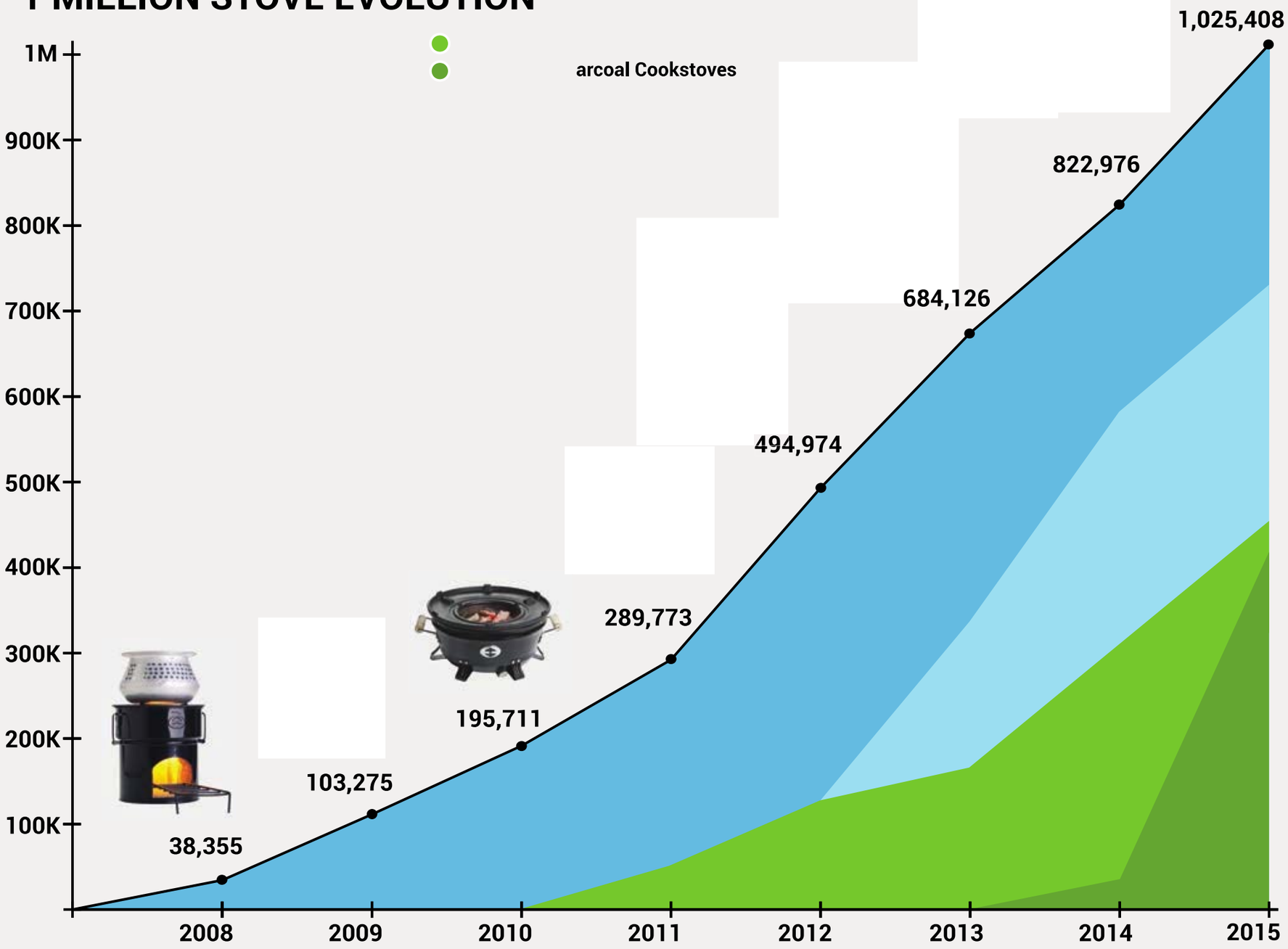
Uganda Stove Factory (Kampala, Uganda, March ‘09)



Gen III Stove

Aspirational - Product that inspires people to want to own

1 MILLION STOVE EVOLUTION




2.5M stoves sold
12.5M lives improved
28M CO_2 emissions prevented
70M trees saved
$200M fuel costs saved
30M working weeks saved
ENVIROFIT

Smart Valve Technology

Envirofit's SIM/GPS SmartGas Valve, enables families to use their phone to prepay for gas as they cook using mobile money.

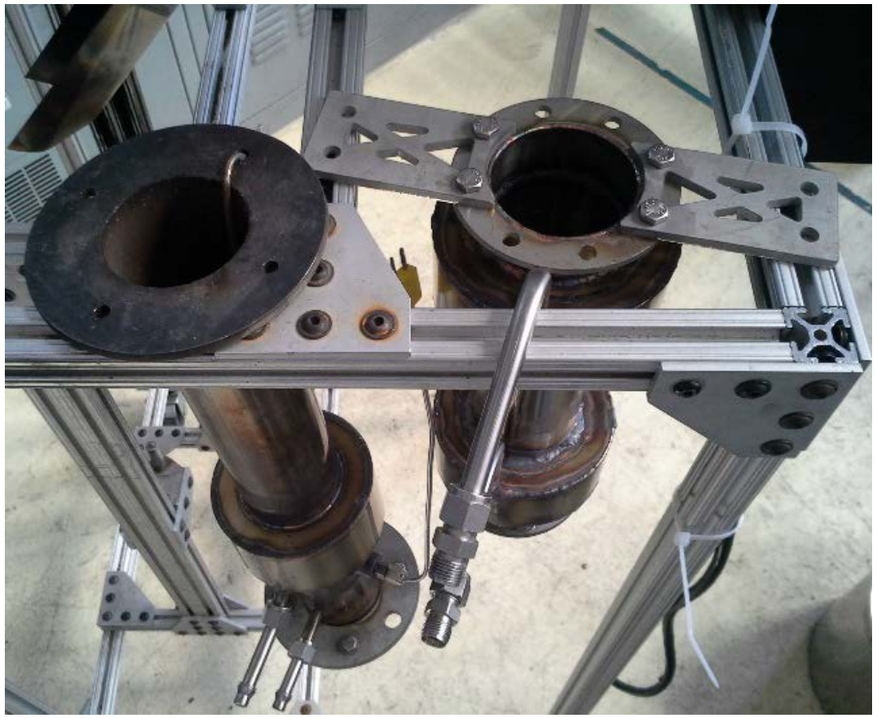
Feces Incineration for Sanitation

Canine Feces

Human Feces

Wood Pellets

Feces Combustor for Sanitation Program



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DOE Advanced Vehicle Design Competitions 1988 - present

951956

Hydrogen for Cold Starting and Catalyst Heating in a Methanol Vehicle

Justin Fulton and Frank Lynch
Hydrogen Consultants, Inc.

Bryan Willson
Colorado State University

ABSTRACT

Hydrogen is unique among alternative fuels in its ability to burn with large amounts of excess air (ultra lean burn) with no carbon-related combustion products. Hydrogen also has a unique ability to burn on the surface of a catalyst, starting from room temperature. Hydrogen may be used in highly "leveraged" ways with other alternative fuels by taking advantage of these unique properties during the crucial period just after the vehicle is started from a cold condition. A methanol vehicle was started on pure hydrogen and idled at ultra lean conditions (oxygen rich exhaust) while injecting hydrogen at the inlet to the exhaust catalyst. Over 15 kW of chemical heating power brought the catalyst to light-off temperature quickly. "Cold 505" transient emissions tests show reductions in all pollutants which far exceed the fraction of the fuel energy supplied as hydrogen.

INTRODUCTION

The work reported in this paper was performed for the National Renewable Energy Laboratory (NREL), Alternative Fuels Utilization Program, Golden, Colorado, under a contract entitled "Advanced Hydrogen/Methane Utilization Demonstration" (Phase II), by Hydrogen Consultants, Inc. (HCI), Littleton, Colorado. Colorado State University's (CSU) Engines and Energy Conversion Laboratory was HCI's subcontractor. Some of the vehicle test work was carried out at the National Center for Vehicle Emissions Control and Safety (NCVECS) at CSU.

Hydrogen is unique among alternative fuels in its ability to burn over a wide range of mixtures in air with no carbon-related combustion products. Hydrogen also has the ability to burn on a catalyst, starting from room temperature. Hydrogen can be made from a variety of renewable energy resources and is expected to become a widely used energy carrier in the sustainable energy system of the future.

One way to make a start toward widespread use of hydrogen in the energy system is to use it sparingly with other alternative fuels. Reductions in emissions greater than the proportion of hydrogen in the fuel provide a form of leverage to stimulate the early introduction of hydrogen. Per energy unit or per dollar of hydrogen, a greater benefit is derived than simply displacing fossil-fueled vehicles with pure hydrogen vehicles.

HYDROGEN COLD-START - This work pursued emissions leverage by using hydrogen with methanol. Methanol, like all liquid fuels, produces most of its toxic and photochemically reactive exhaust emissions during the first few minutes after a "cold" motor vehicle is started. These "cold-start" emissions can be greatly reduced by starting the vehicle on hydrogen. In the ultra leanburn mode (λ>3), a hydrogen fueled engine's exhaust is very clean and has a high oxygen concentration.

HYDROGEN HEATED CATALYST - After a methanol vehicle reaches operating temperature it depends on a three-way catalyst for emissions control. The amount of time required for the catalyst to reach operating temperature may be reduced by actively heating it, rather than waiting for the exhaust to do so. In addition to starting and idling the engine on hydrogen, additional hydrogen was injected into the oxygen-rich exhaust stream. The hydrogen and oxygen burned on the surface of the catalyst, heating it directly. A chemical heating power of 15.1kW was applied in the tests discussed below.

EMISSIONS TESTING - The benefits of hydrogen cold-start and heating the catalyst with hydrogen were investigated using Phase I of the Federal Light-Duty Vehicle Emissions Test (FTP). These tests, commonly called "Cold 505s," were conducted with CSU's award-winning Methanol Marathon competition vehicle. The usual battery of instrumentation in the NCVECS laboratory was supplemented by a Fourier Transform Infrared (FTIR) analyzer.

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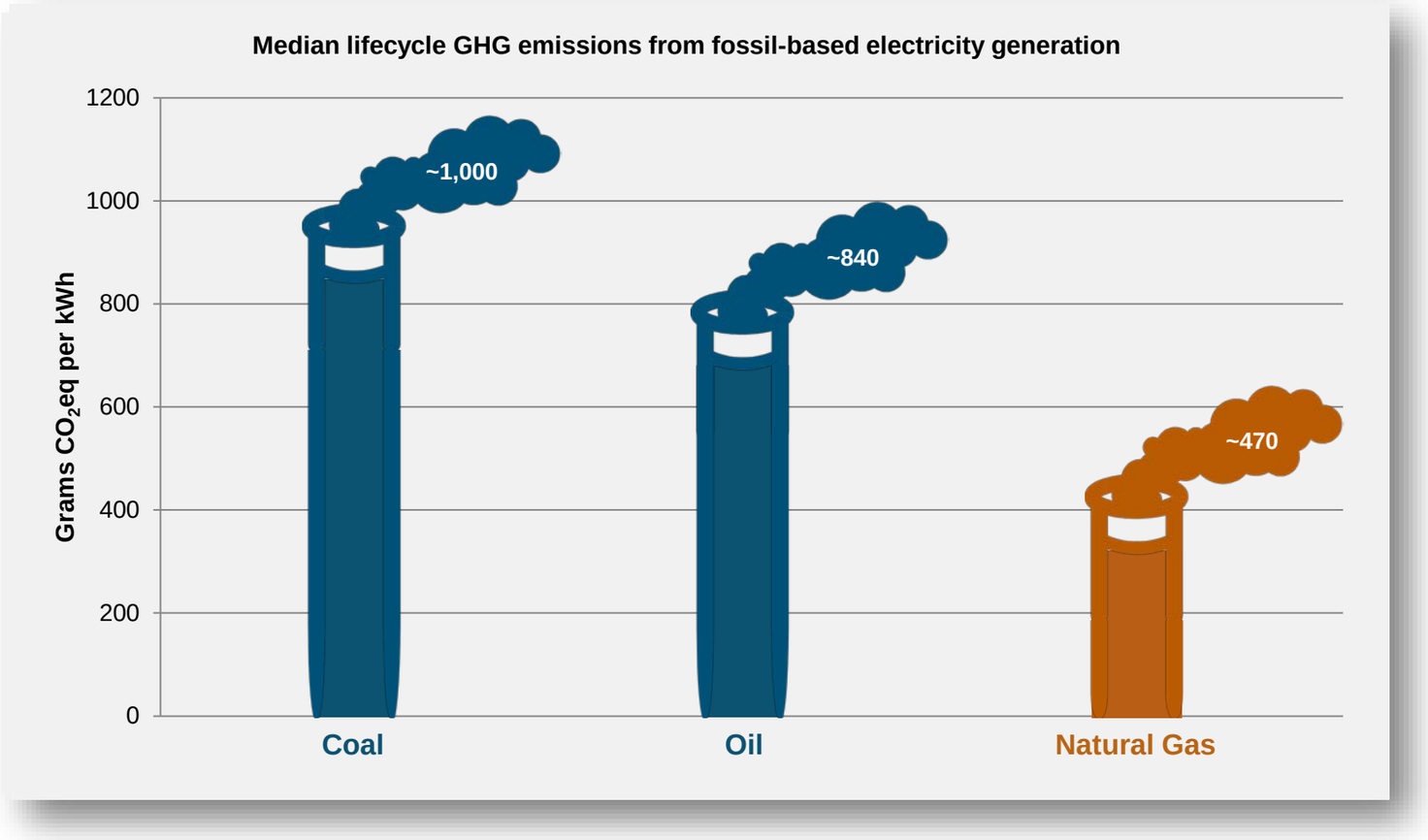
Molecule

Methane: The Official Molecule of the Powerhouse Energy Campus

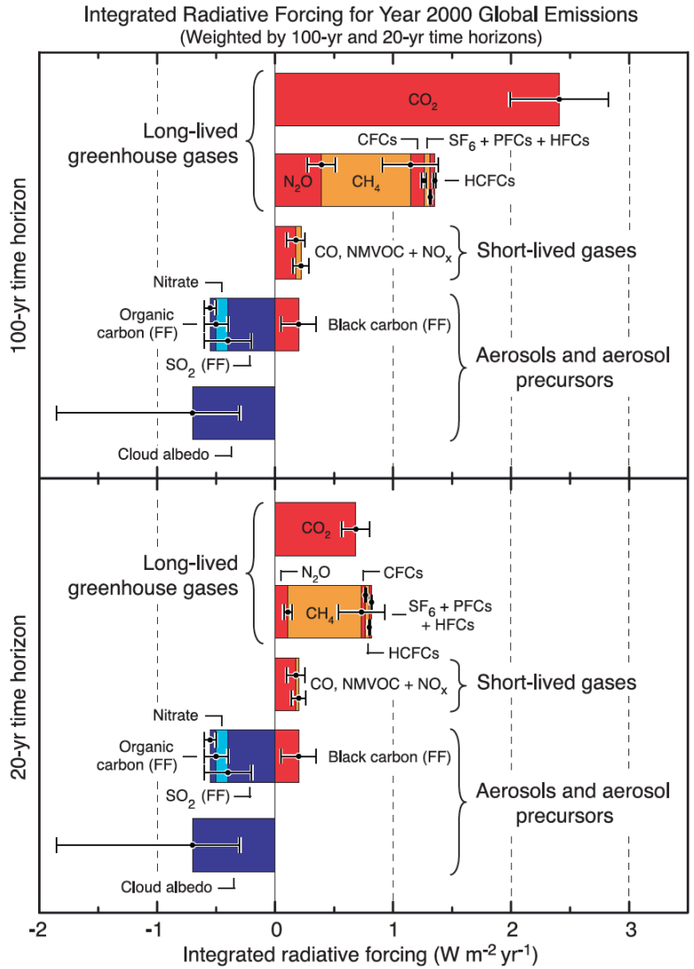
The Environmental Case for Natural Gas

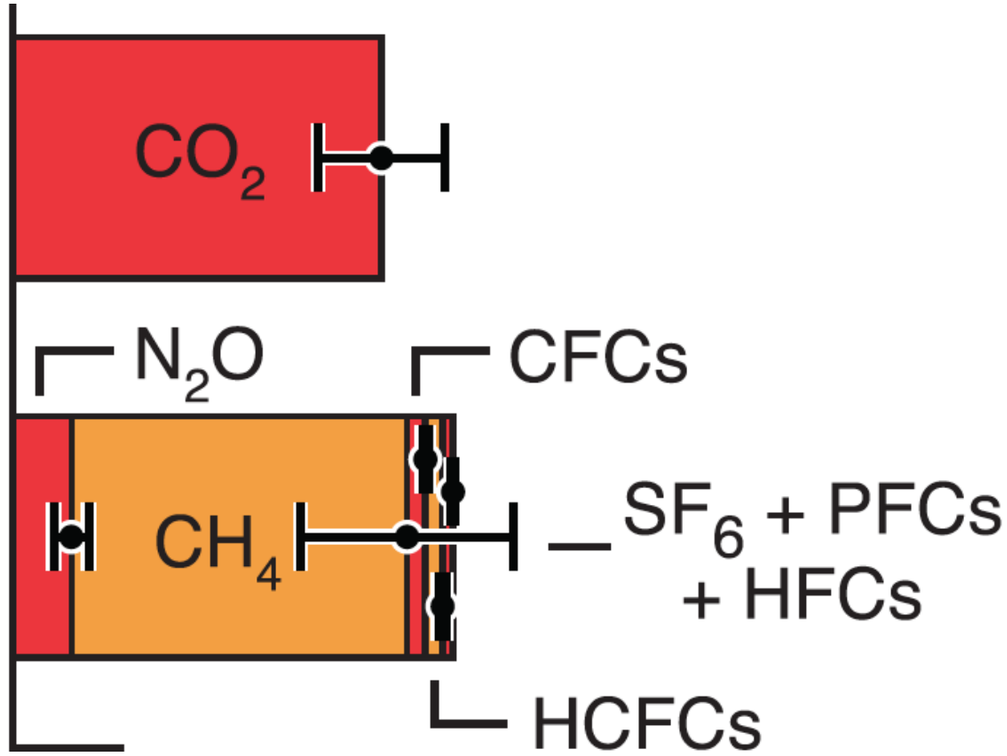
On a lifecycle basis, natural gas emits nearly half the level of greenhouse gases as coal when burned; the challenge is ensuring that environmental risks throughout the supply chain are effectively mitigated



Source: IPCC AR4 Annex II (2007)

In the near-term, global radiative forcing by CH_4 & CO_2 are similar





AR4, p 206

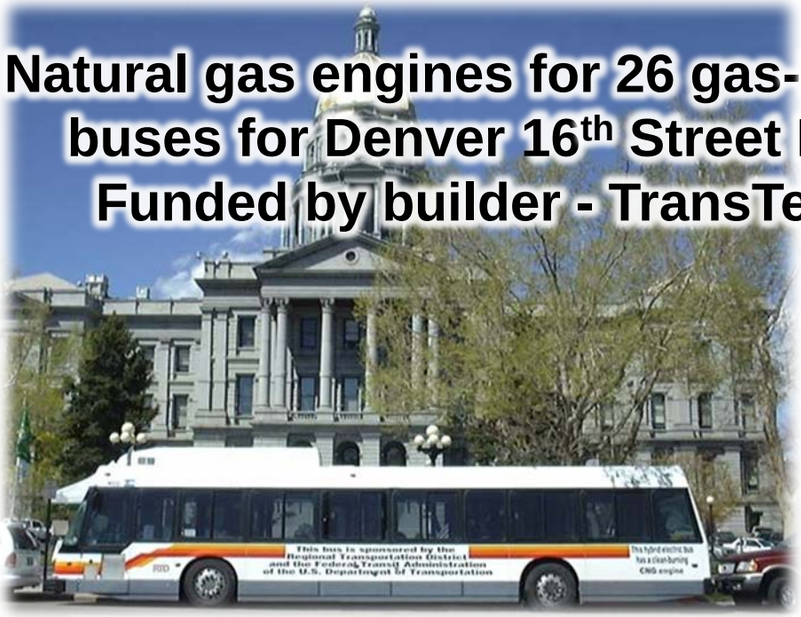
Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Early Natural Gas Engine & Vehicle Development

Optimized CNG Truck for DOE AVRC

1600 hp natural gas engine for World Land Speed Record – funded by GRI

"Hythane" (H_2/CH_4) Engines & Vehicles



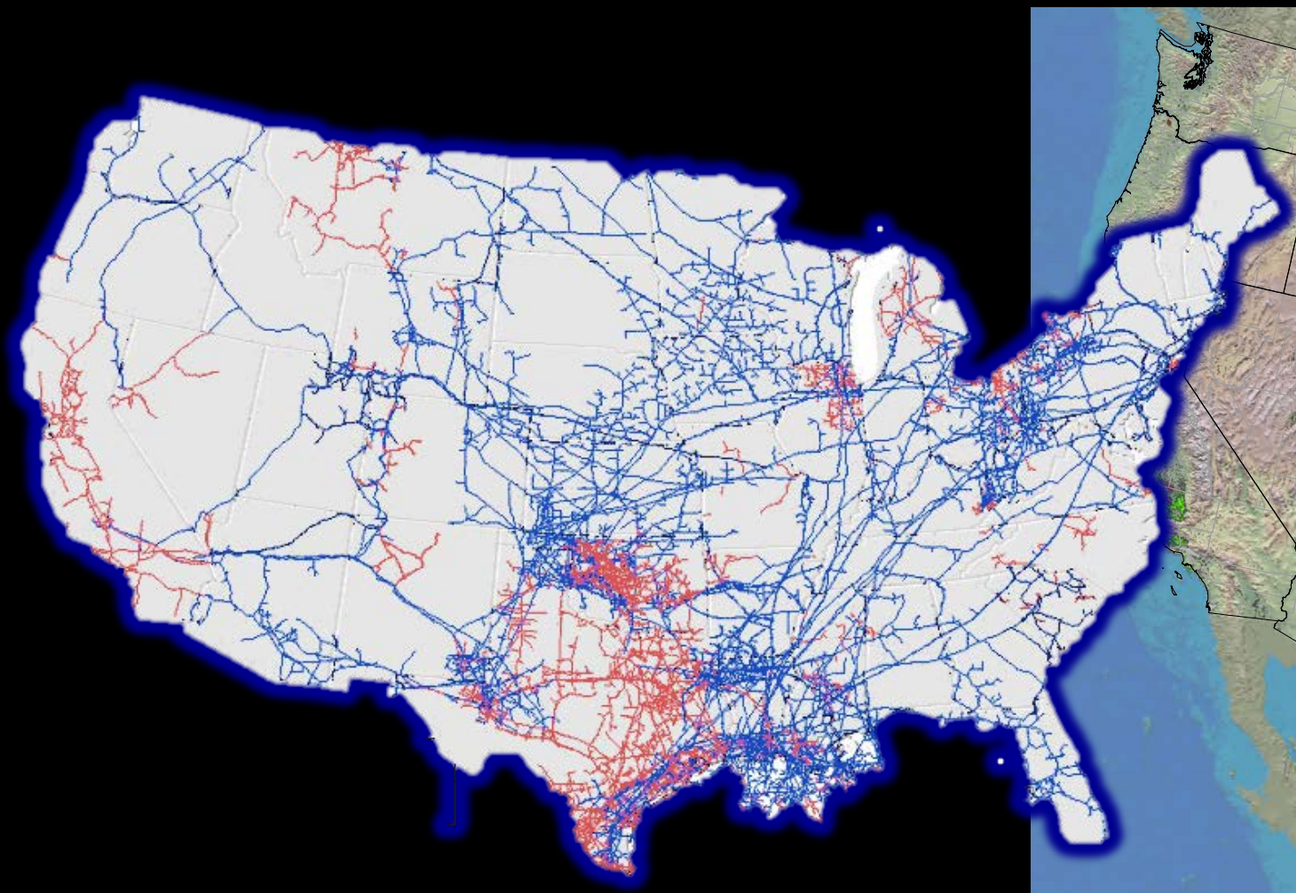
Natural gas engines for 26 gas-hybrid buses for Denver 16th Street Mall Funded by builder - TransTech

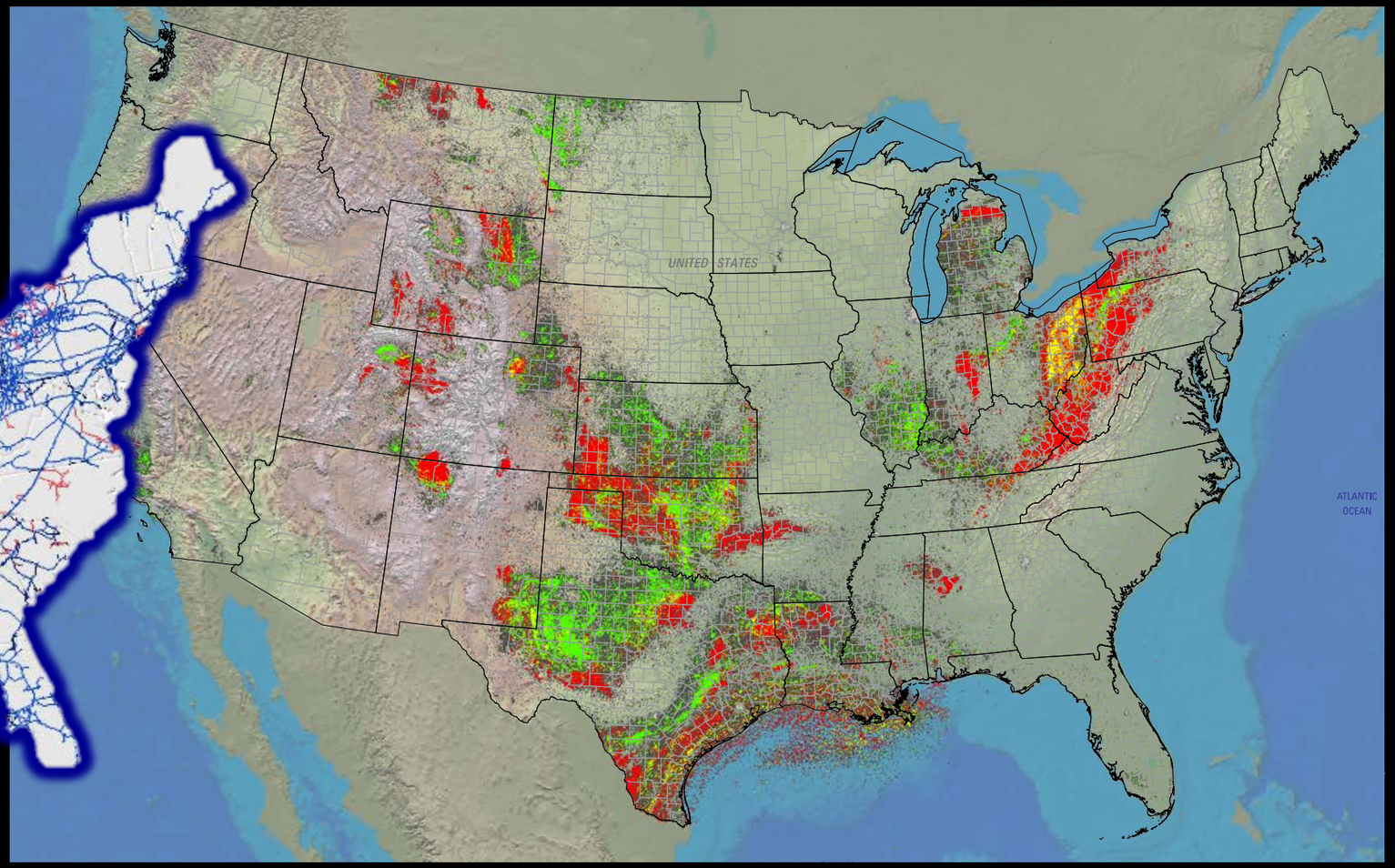
Natural gas engines for 3 Pikes Peak Hill Climb cars – funded by INGAA

Natural gas engine for World Land Speed Record

- 550 in^3
- Dry liner
- Series turbocharging
- Methanol / dry ice intercooler
- 2300 hp verified design output
- 1600 hp in current configuration
- 332 mph in 2009

2.7 million wells drilled in the U.S.
900,000 in current production
350,000 miles of pipelines





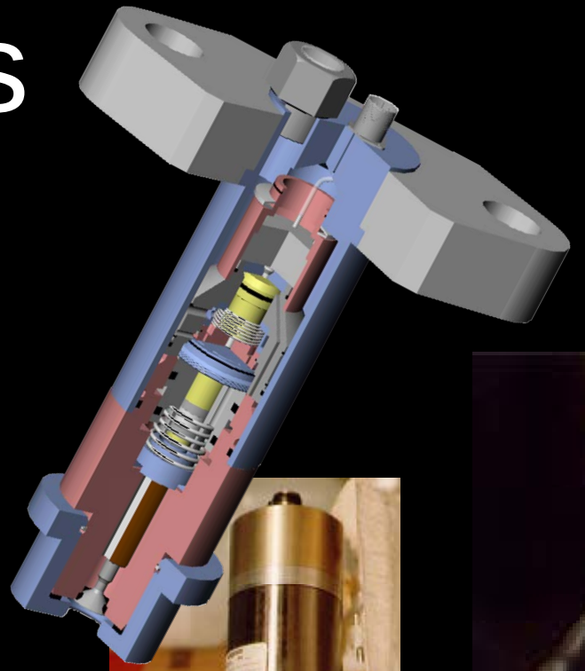
Typical Natural Gas Compression Engines

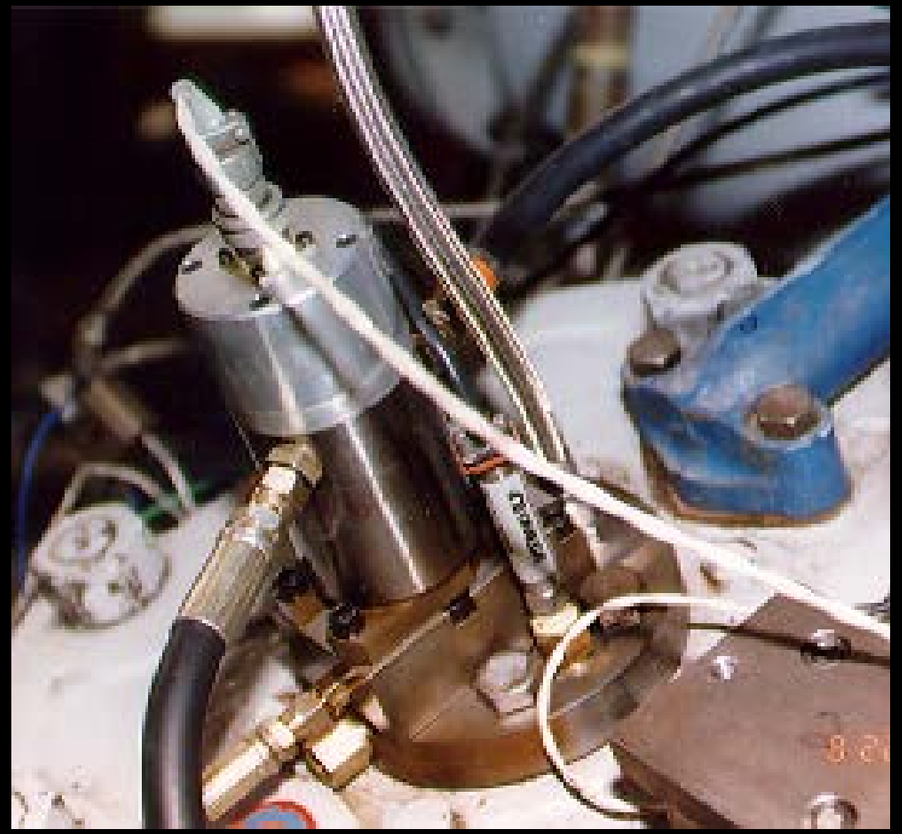
Large Bore Engine Testbed, 1992

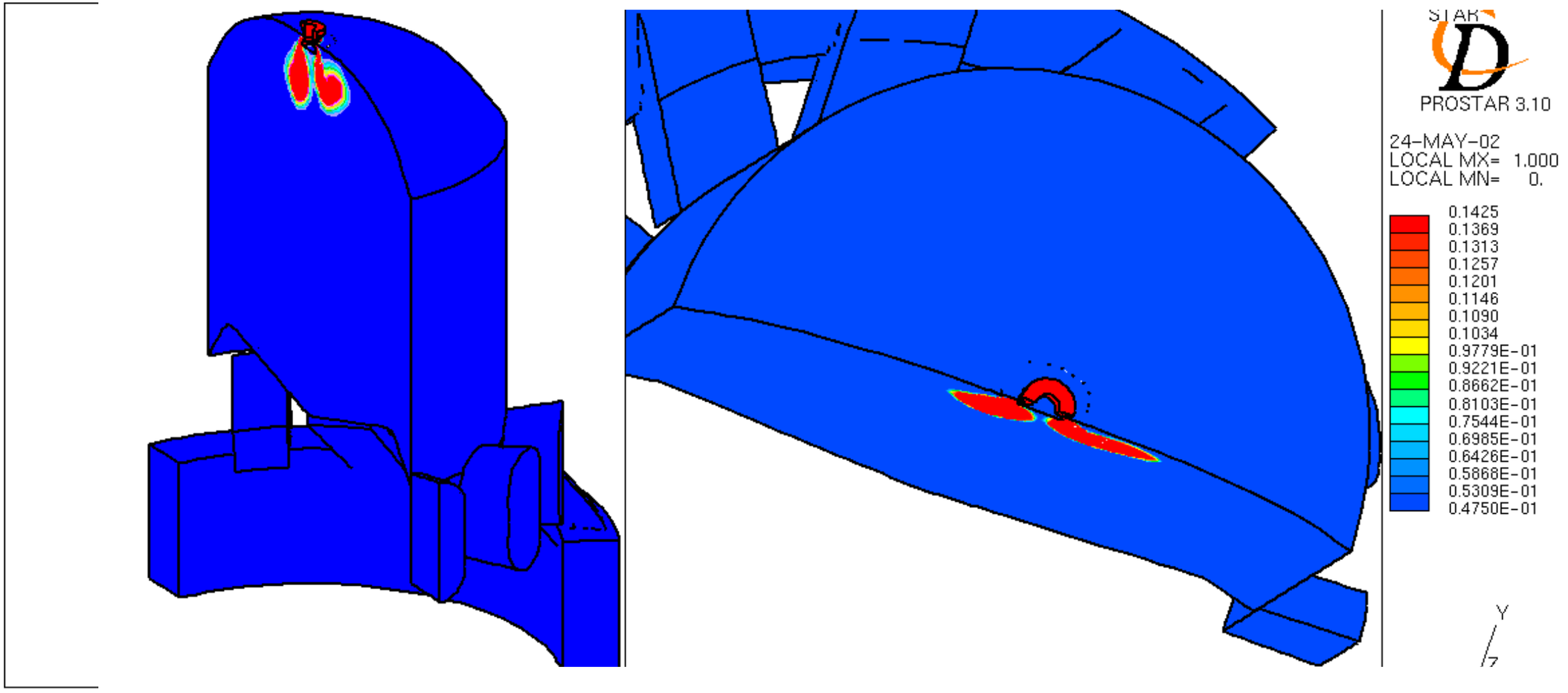
Early EECL Motto

Go Big
or
Go Home

High Pressure Fuel Injection for 2-Stroke Engines



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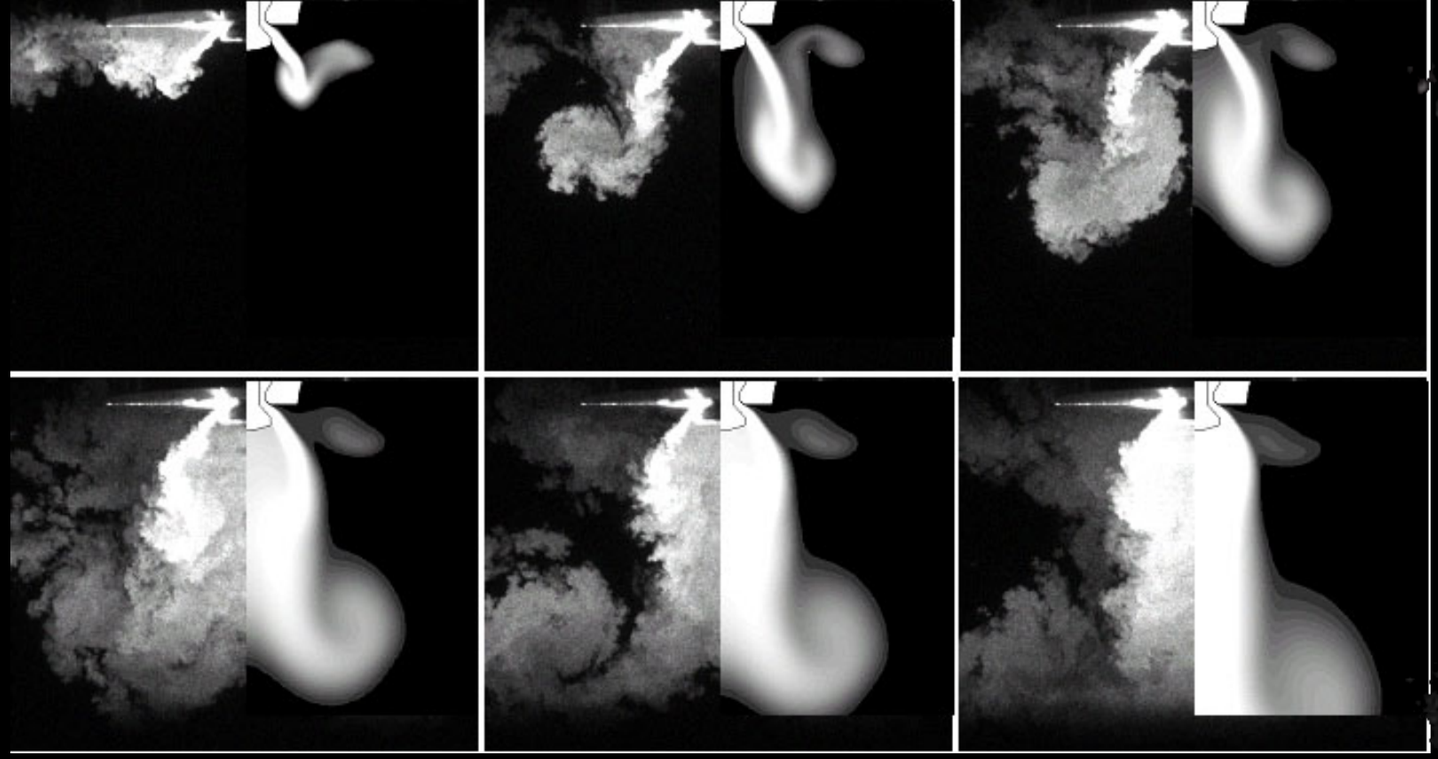
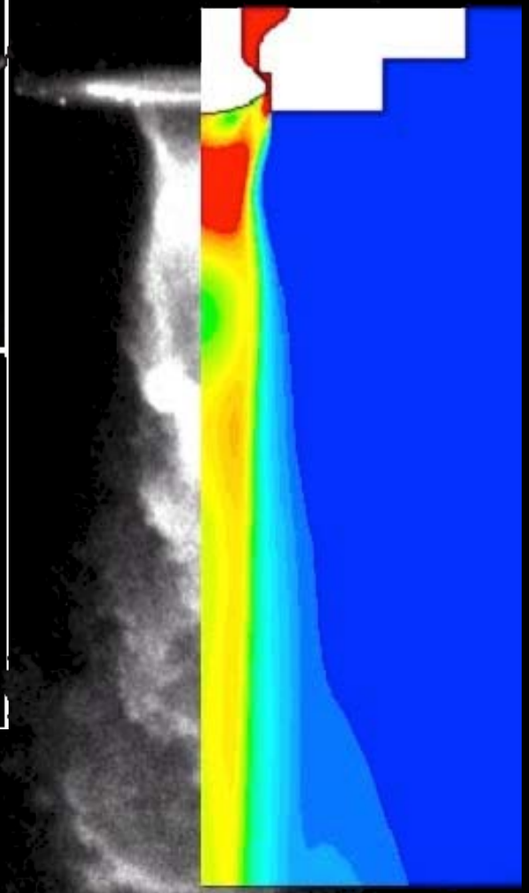
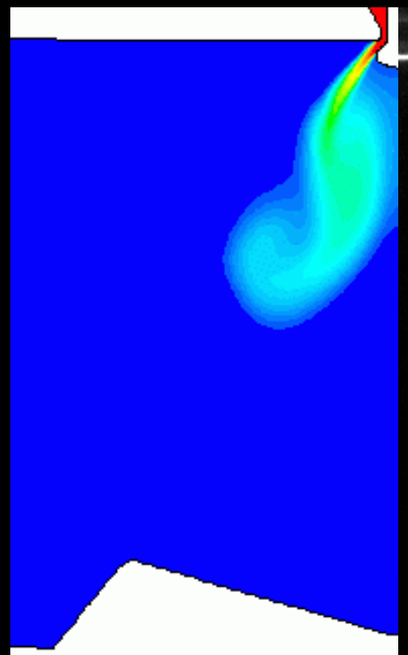
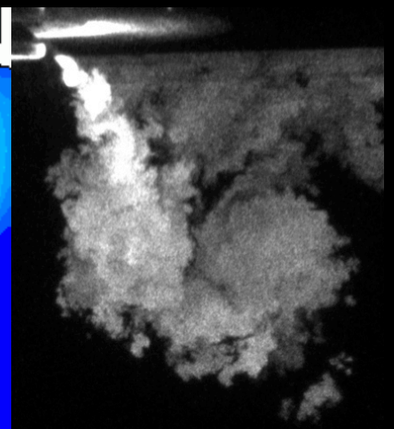


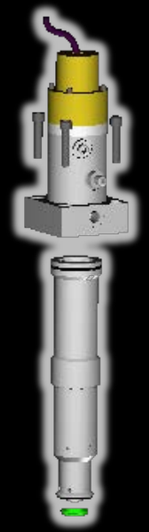


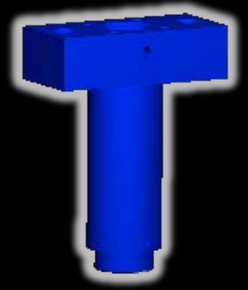




CFD Results with PLIF Validation

Annual NOx Savings from EECL Technologies = 150,000,000 Autos





Large Engines at the EECL


Cooper-Bessemer GMV


Waukesha VGF


Cat 3508 Diesel

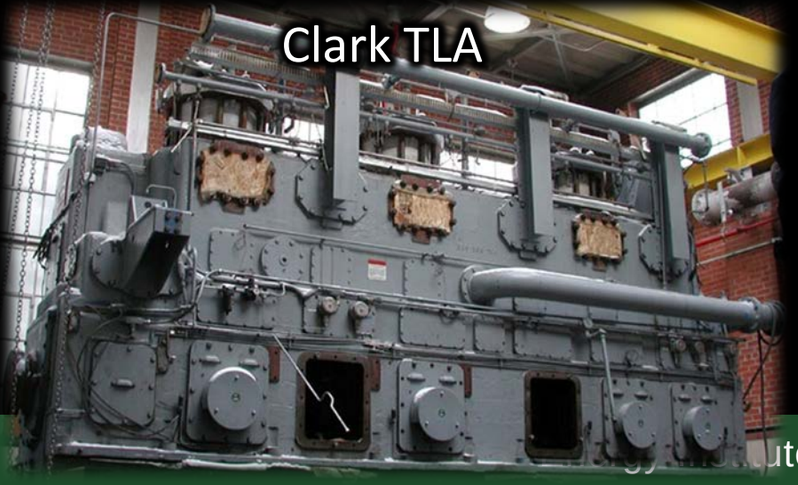

Cummins QSK


Superior

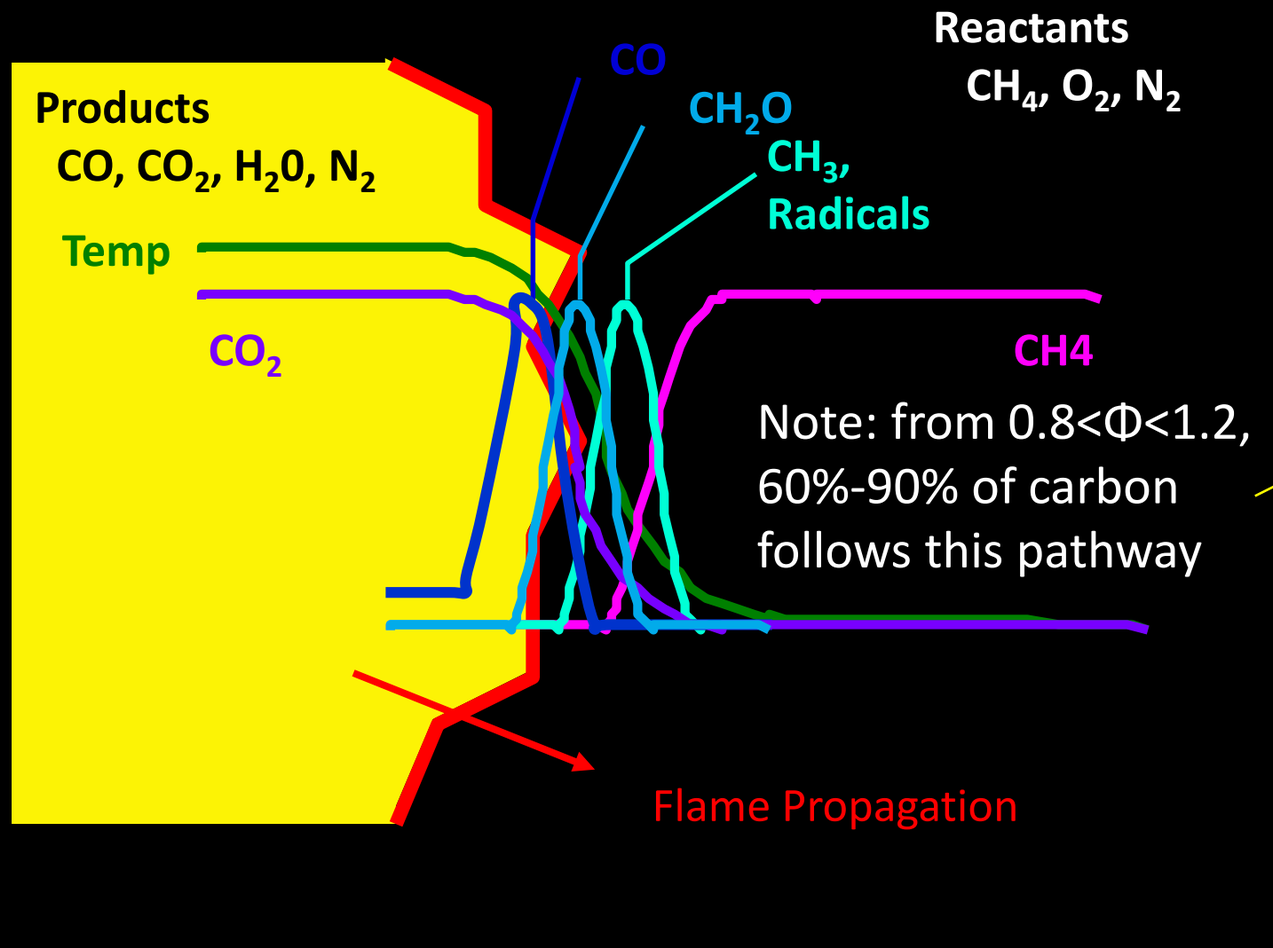

Waukesha VHP

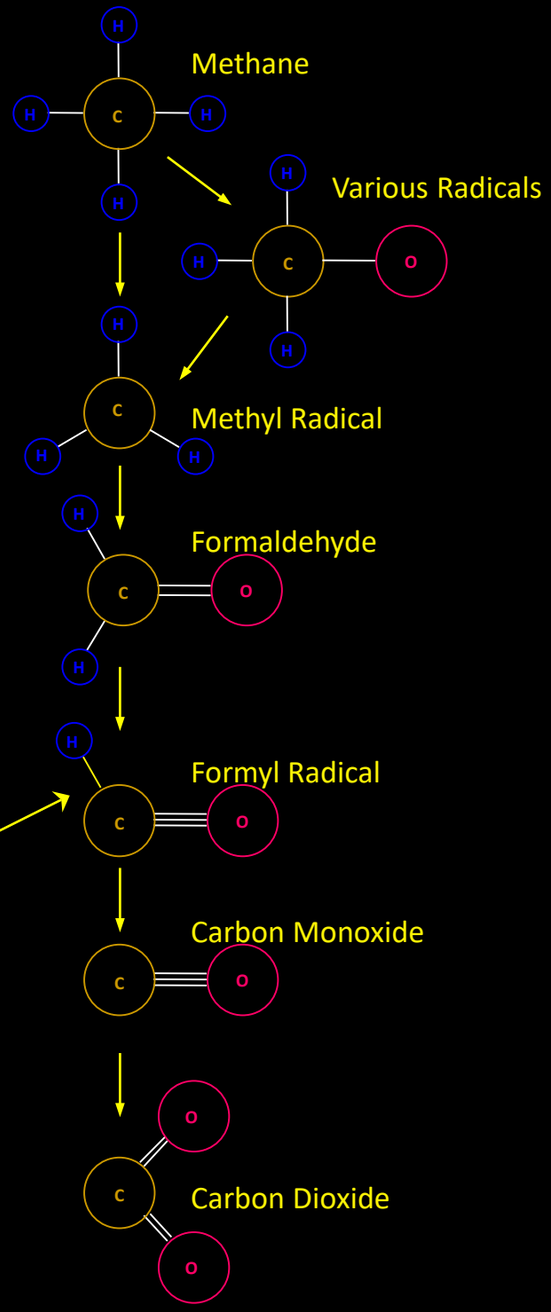

Manx Engine

Cat 3516C NG

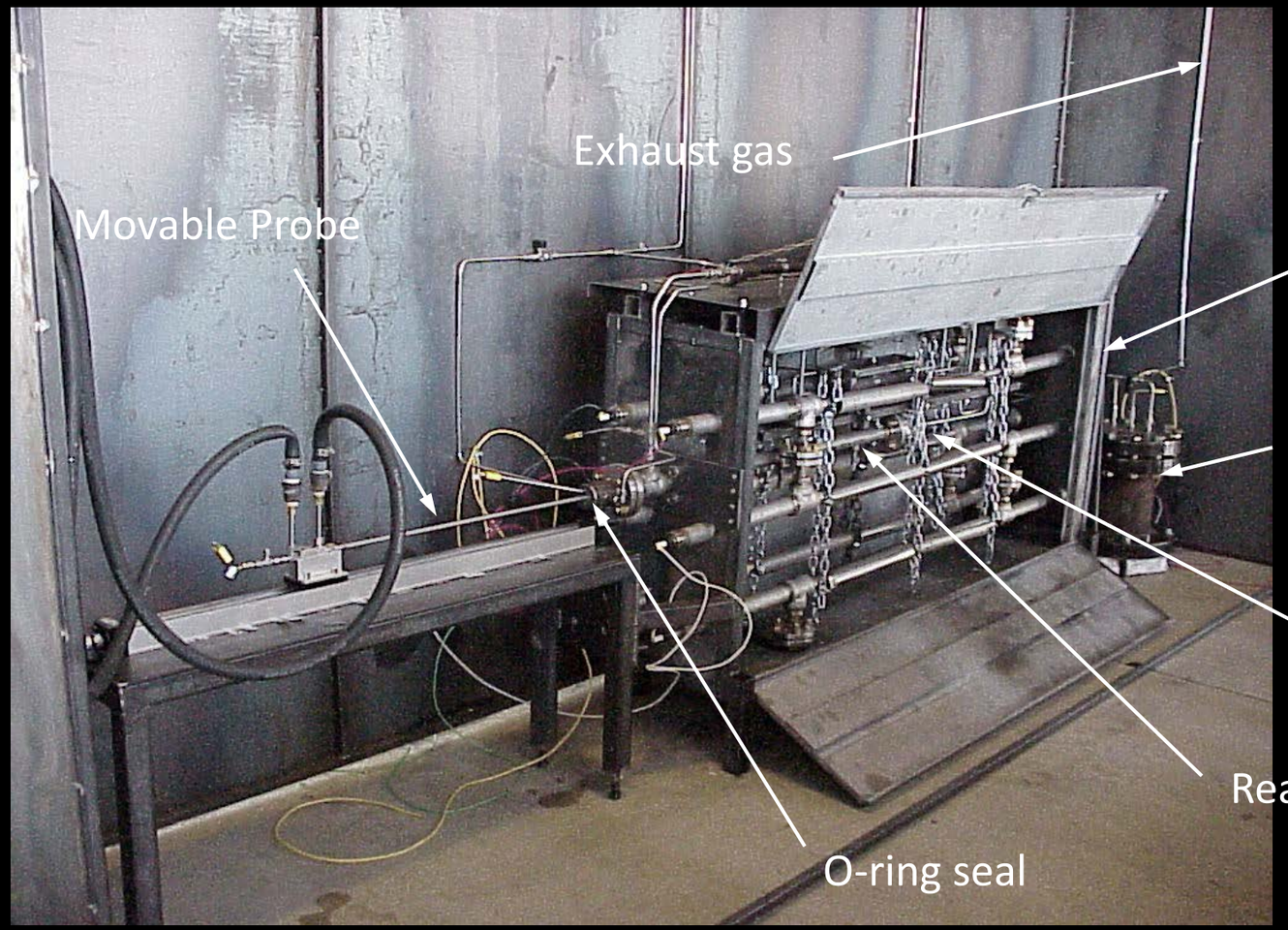

Clark TLA

Natural Gas Combustion / CH_2O Formation



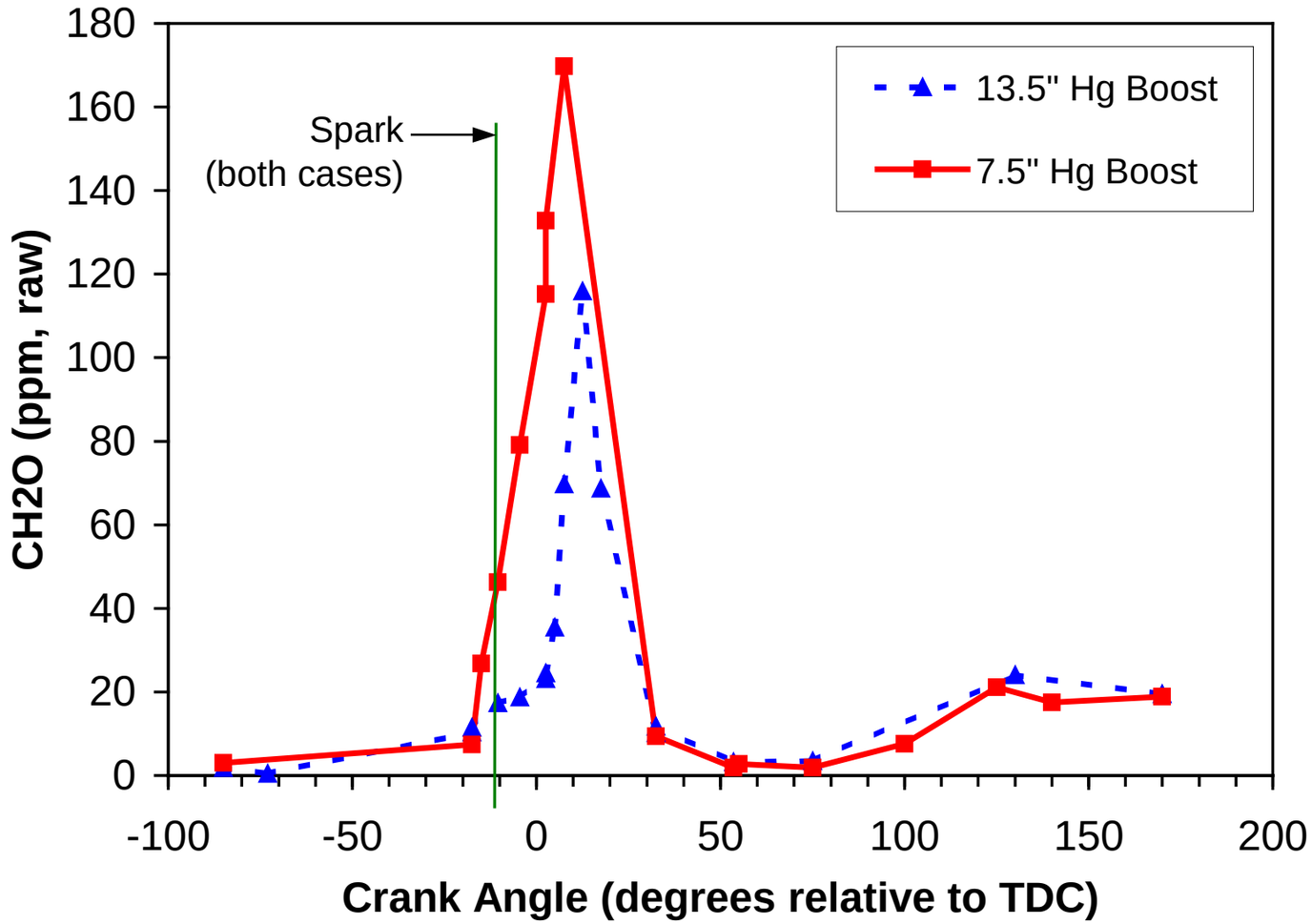


Chemical Kinetics –
Test Facility Development



Probe-Reactor-Heater Assembly

Crank Angle Resolved Formaldehyde Fast Sample Valve Measurements



Scientific Support for ICCR Process, NESHAP / MACT Rule for HAPs (Hazardous Air Pollutants)

6560-50-P

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Part 63

[EPA-HQ-OAR-2008-0708, FRL-XXXX-Y]

RIN 2060-AQ58

National Emission Standards for Hazardous Air Pollutants for Reciprocating Internal Combustion Engines; New Source Performance Standards for Stationary Internal Combustion Engines

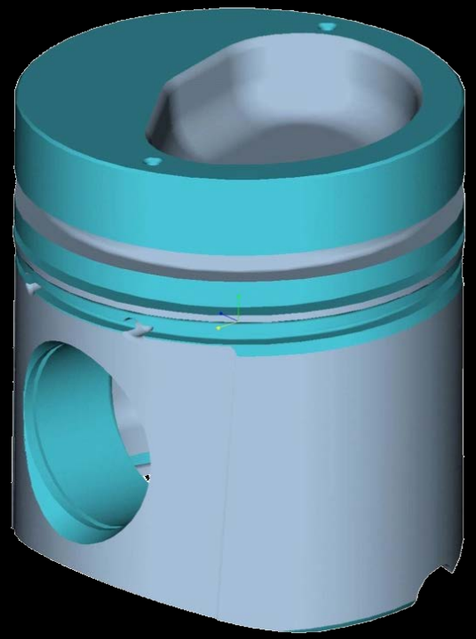
AGENCY: Environmental Protection Agency (EPA).

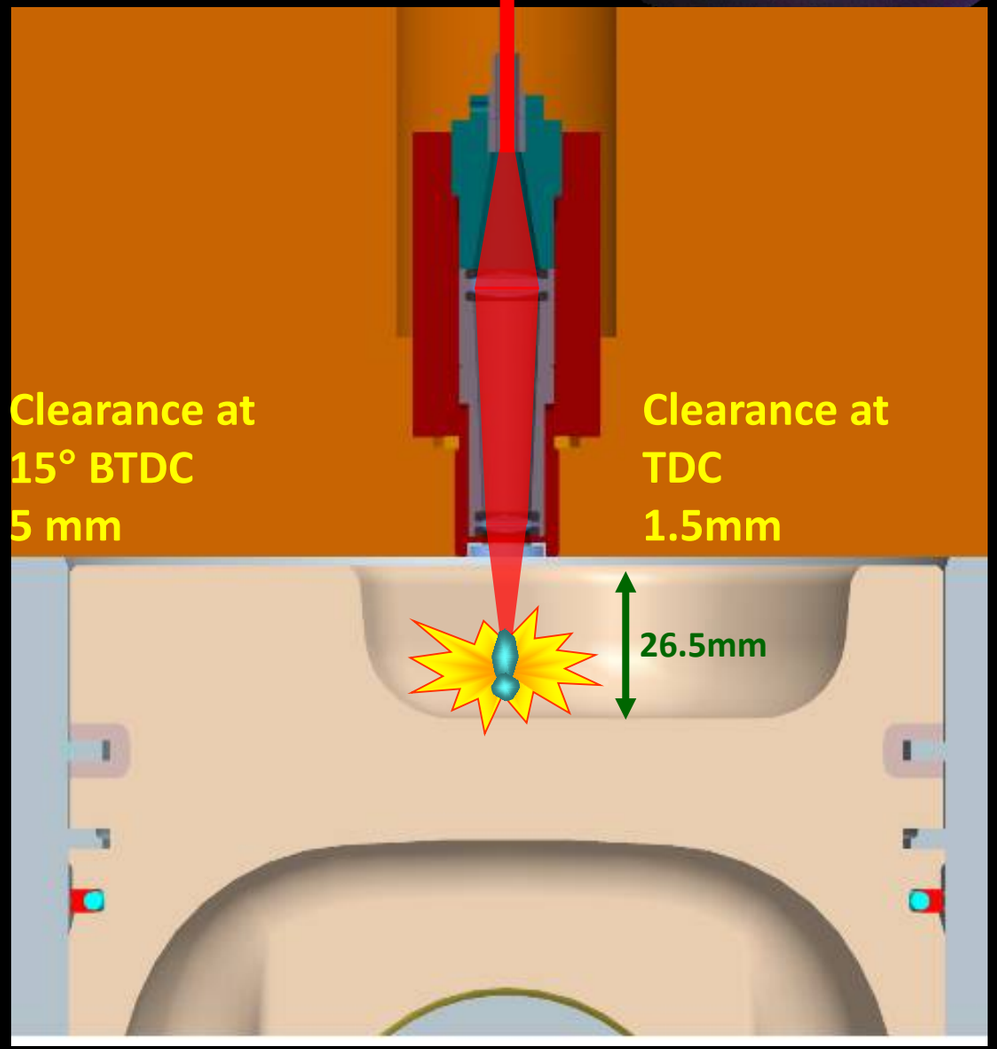
ACTION: Proposed rule.

SUMMARY: The EPA is proposing amendments to the national emission standards for hazardous air pollutants for stationary reciprocating internal combustion engines under section 112 of the Clean Air Act. The proposed amendments include alternative testing options for certain large spark ignition (generally natural gas-fueled) stationary reciprocating internal combustion engines, management practices for a subset of existing spark ignition stationary reciprocating internal combustion engines in sparsely populated areas and alternative monitoring and compliance options for the same engines in populated areas. The EPA is also proposing to include a limited temporary allowance

Pulsed
Nd:YAG Laser

Laser Spark Ignition





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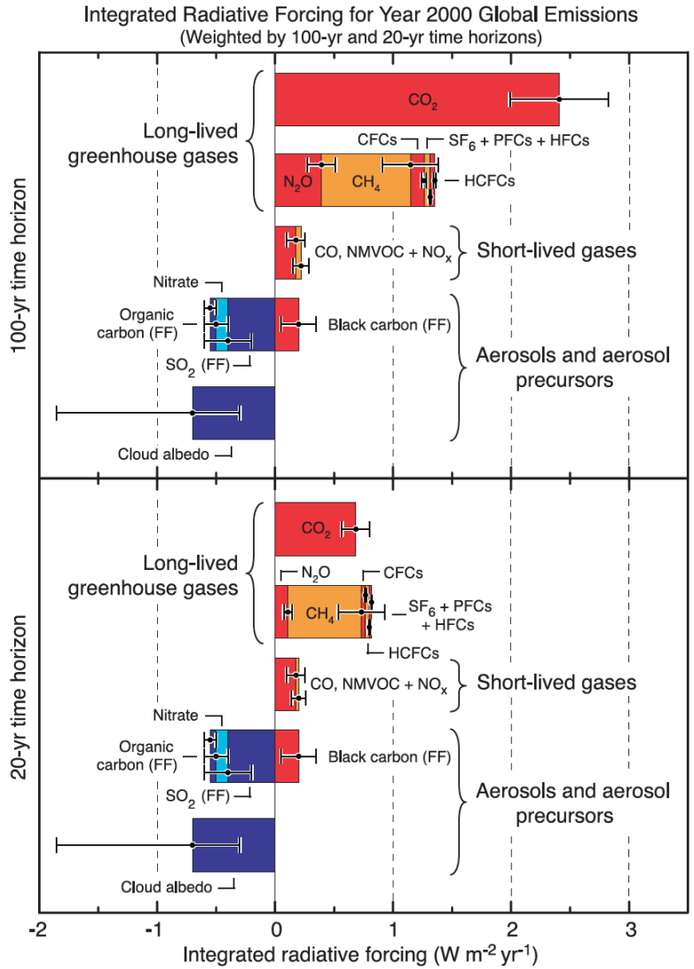
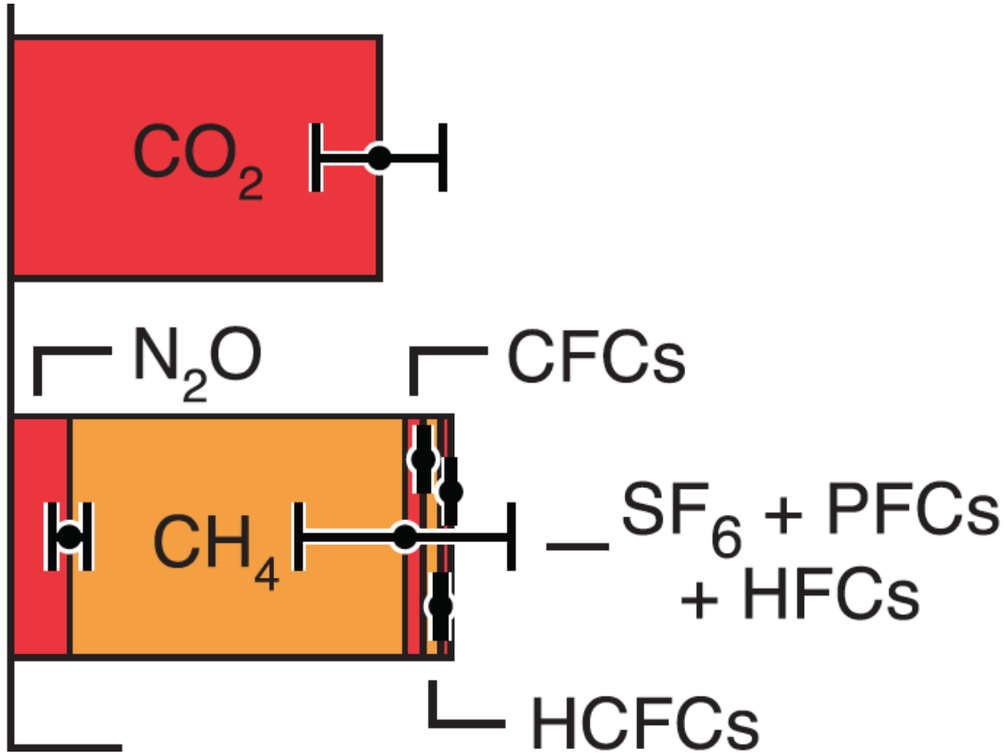


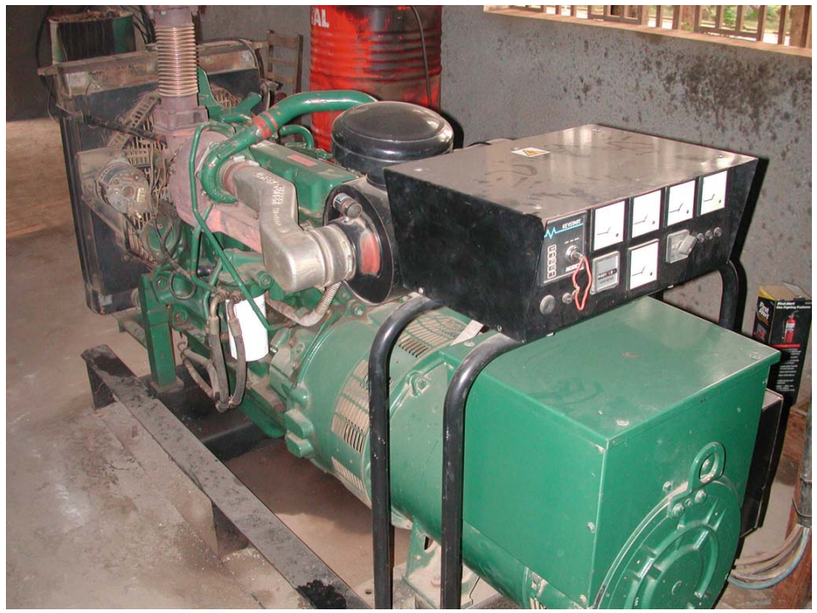


AR4, p 206

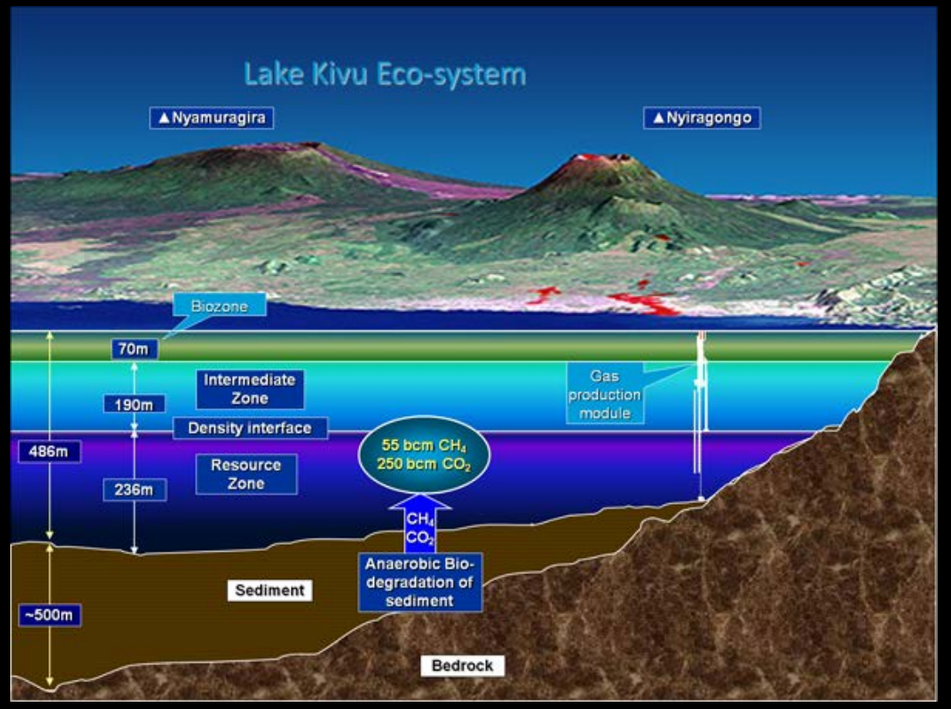
Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

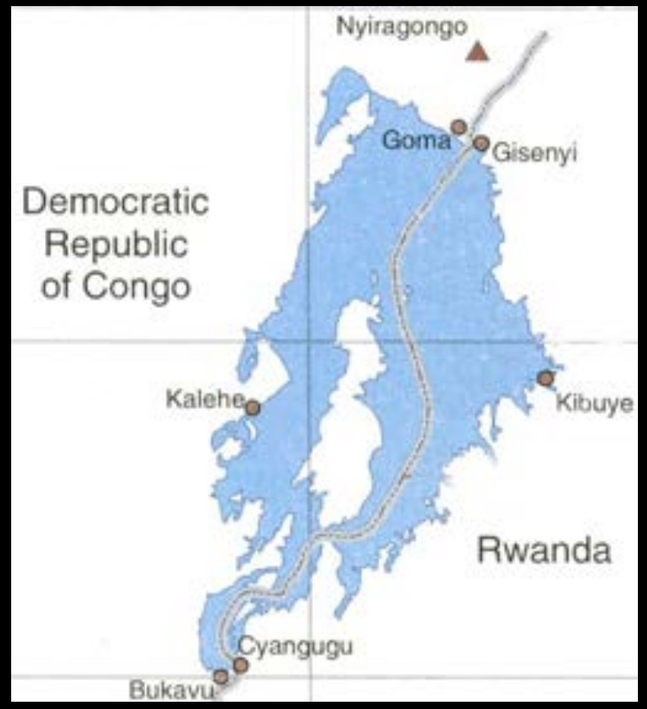
Methane Emissions Technology Evaluation Center

Methane can be a highly sustainable fuel



Productive Uses of Lake Kivu Methane





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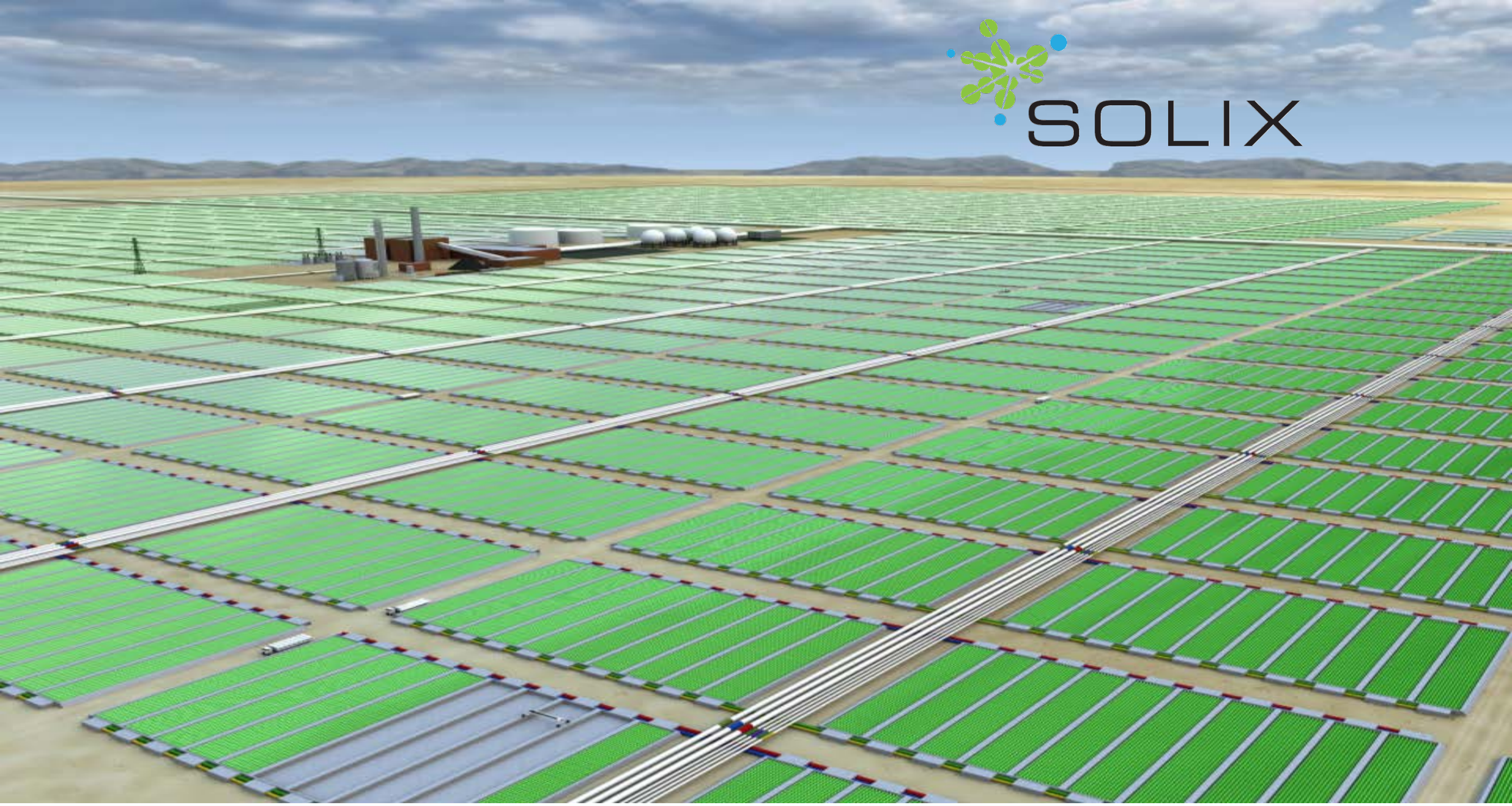
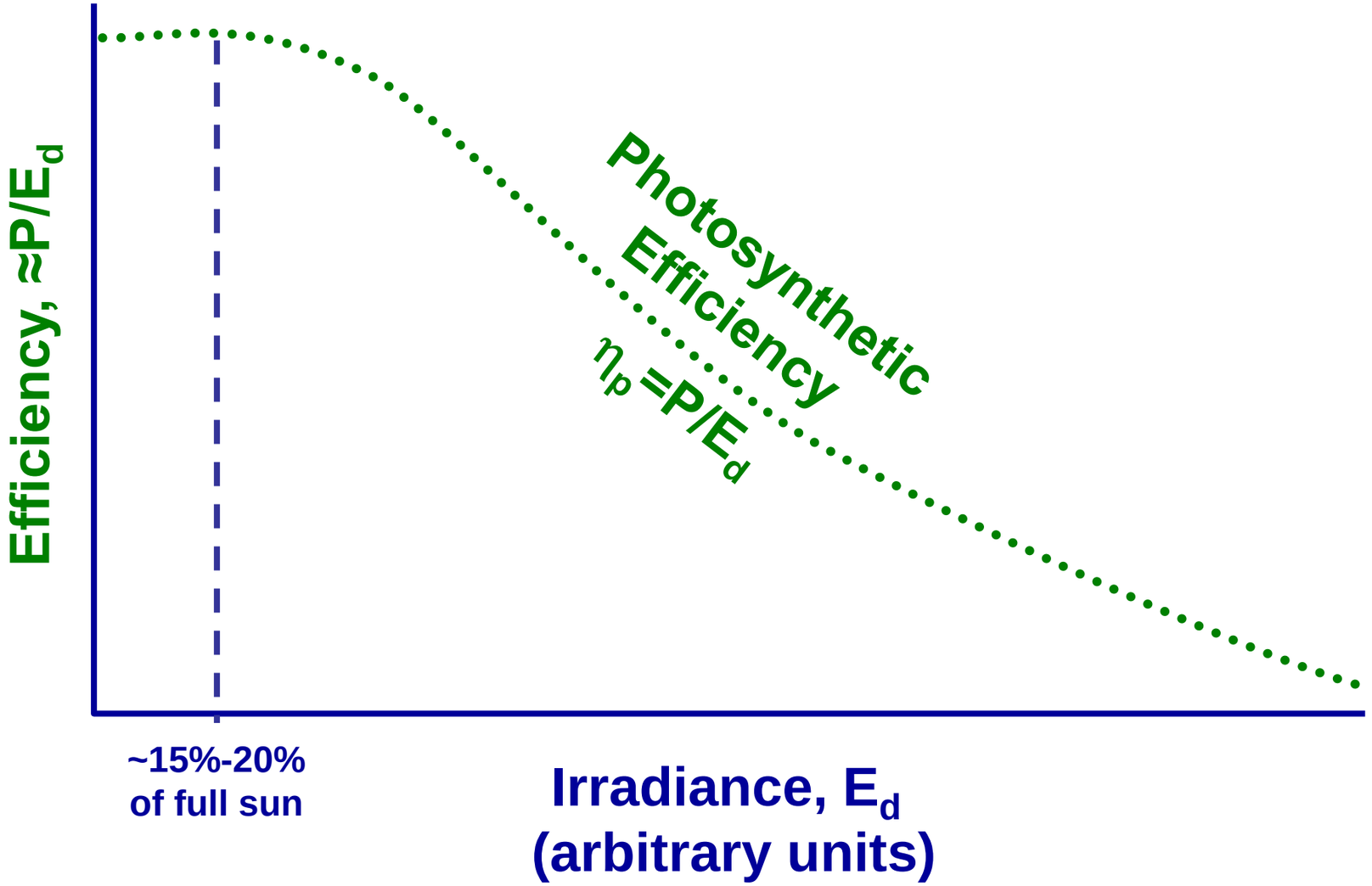
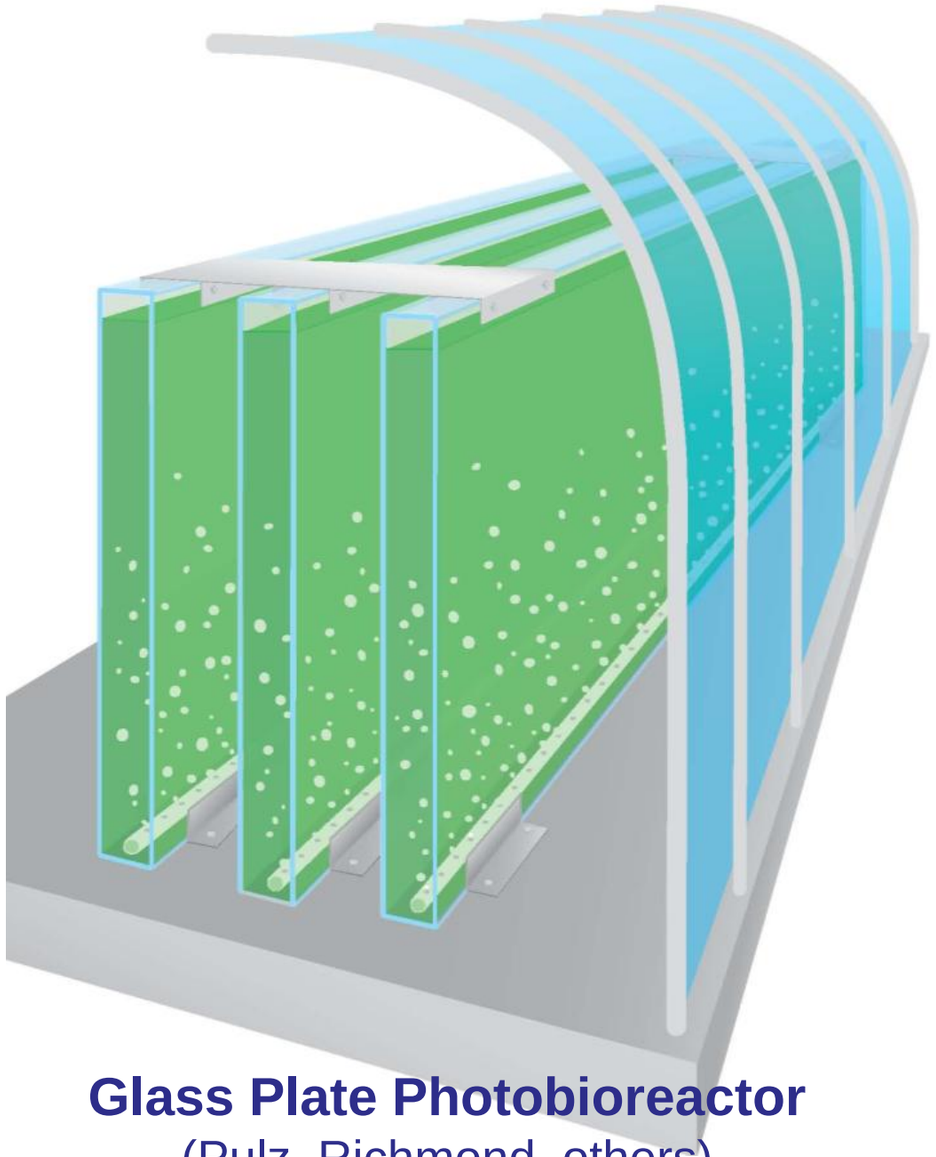
- **Algae-based biofuels**
- Hydrogen


SOLIX

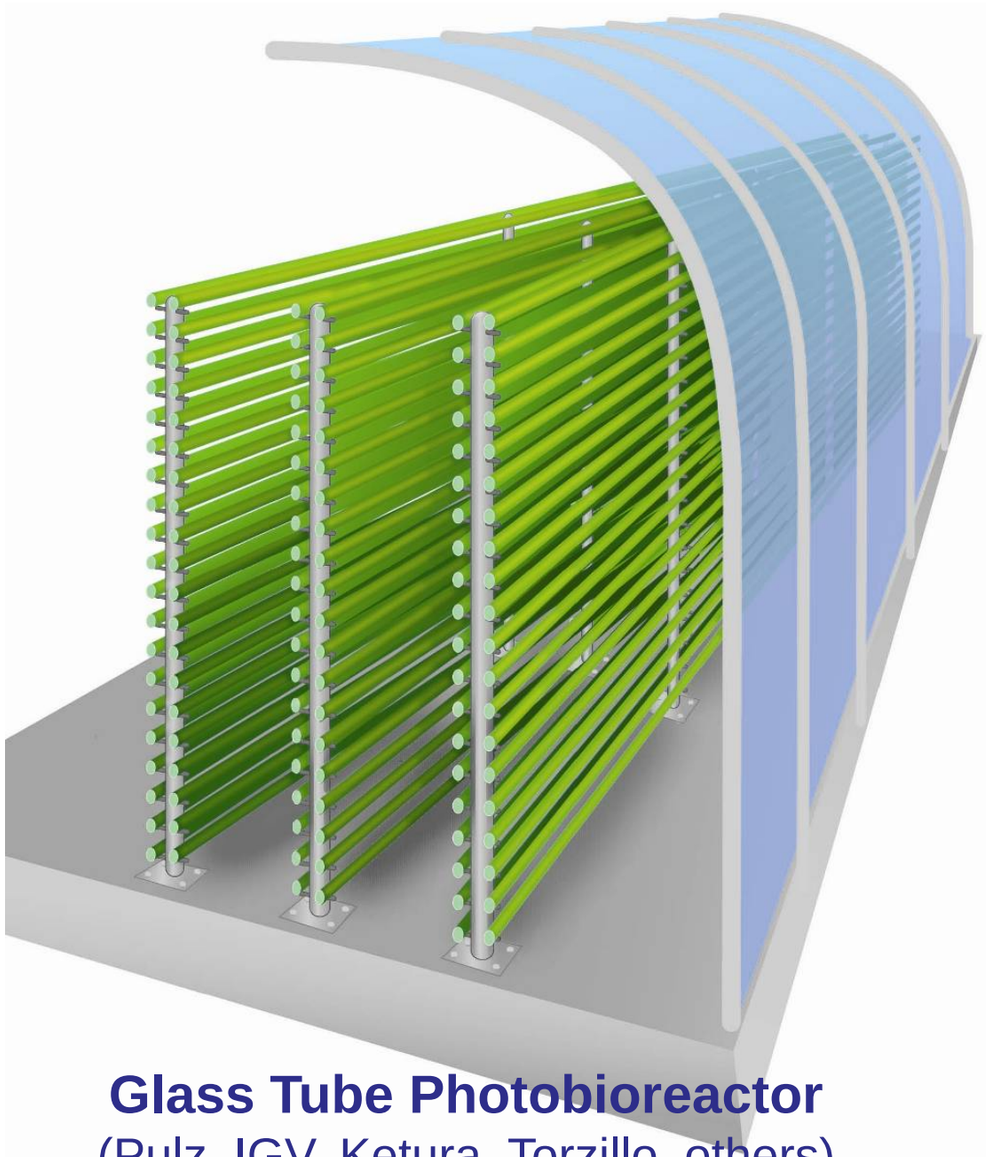
Photosynthetic Efficiency



Extended Area PBRs

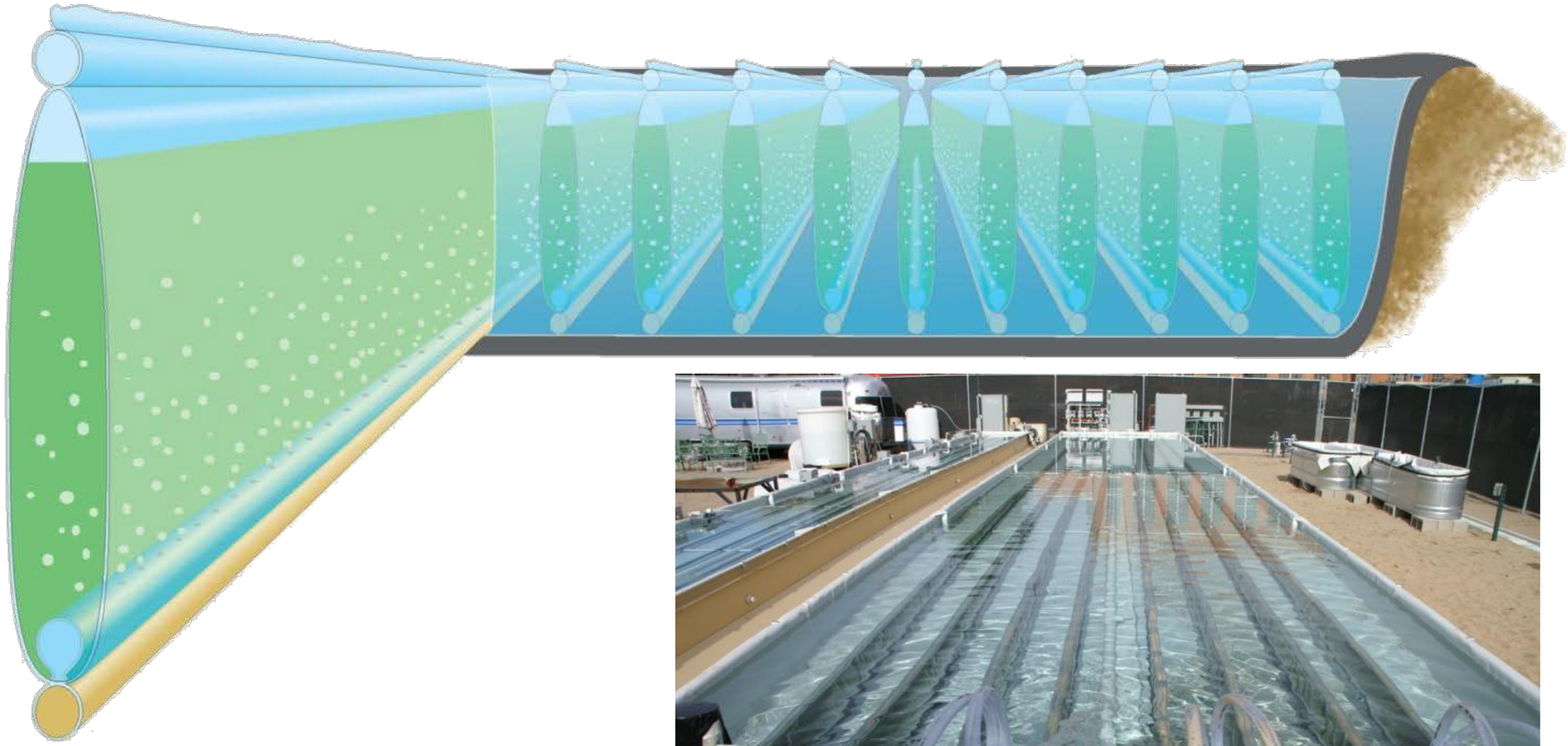


Glass Plate Photobioreactor
(Pulz, Richmond, others)



Glass Tube Photobioreactor
(Pulz, IGV, Ketura, Torzillo, others)

Photo-bioreactor (G3)



Solix G3 Technology:

- Extended surface area
- Water supported
- Integrated CO_2 / air sparging
- G4 – membrane exchange in development

Outline

- Engines & Energy Conversion Lab
- Biomass
- Alcohols
- Natural gas
- Algae-based biofuels
- **Hydrogen**

Renewed Interest in H_2/CH_4 Fuels

H_2 Addition "Hythane"

- Sponsored by DOE/NREL
- Partnership with Frank Lynch (Hydrogen Components Inc.)
- Engine & vehicle tests
- Lean & stoichiometric
- Showed significant improvement & extension of the lean limit with 10% H_2 (by energy)
- Now widely accepted, new station in Ft. Collins, big effort in China

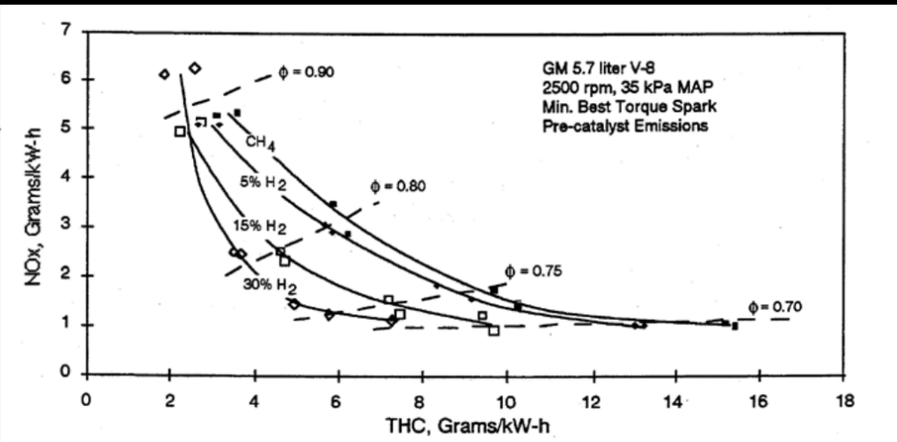
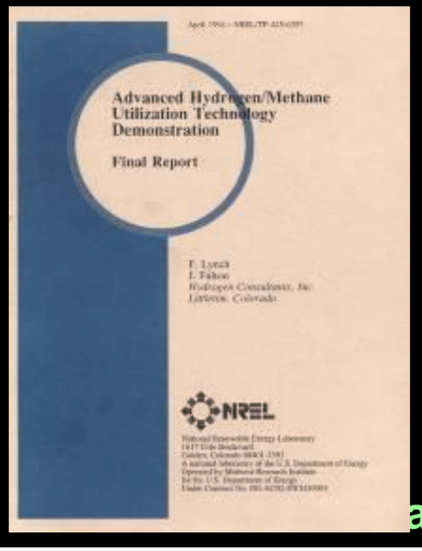
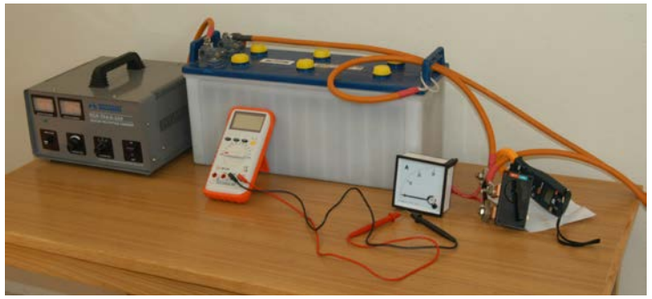
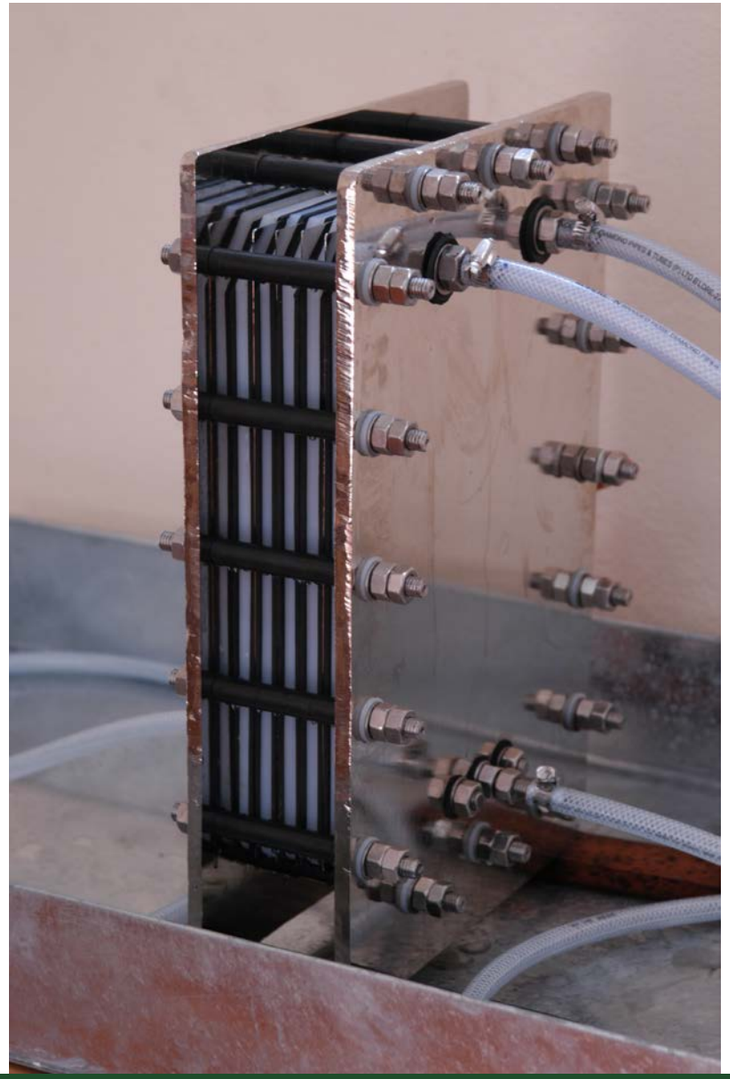


Figure 4-11. At any given NOx level, THC emissions are significantly less with Hythane. The dashed lines indicate the equivalence ratio corresponding to each set of points.



H_2 Electrolyzer Lab - Kathmandu, Nepal





2-Stroke Direct Injection H_2 Engine

CSU Hydrogen Hybrid Fuel Cell Vehicle

CORFO

INTERNATIONAL CALL FOR:
Technological Institute, for solar energy, low emission mining and advanced materials of lithium and other minerals

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Moving H_2 into Mining Vehicles in Chile
Diesel – Battery - H_2 Fuel Cell


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NREL

Loading in Washington DC on Friday, 9/25/20

Compressor, Storage, Dispensing Unit

Electrolyzer Unit

Cooling Skid

Offloading at Powerhouse

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