Environmentally Friendly Drilling

EFD

PbNG™
POWERED BY NATURAL GAS

IADC®

"The New Age in Drilling"

Q2 IADC DEC Technology Forum

June 13, 2018

Apply Data Science for Rapid Modeling of Dual Fuel Technology for Life Cycle Assessment

Revised to include Dual Fuel Diesel Savings Information, June 28, 2018.
Please see accompanying proposal materials for details.

Carolyn J. LaFleur, M.Eng, P.E.
Research Scientist

Fanxu Meng, Ph.D, P.E.
Research Associate

HARC (härk), *n.*
an independent research hub helping people thrive and nature flourish.

Houston Advanced Research Center
The Woodlands, Texas
www.harcresearch.org

Environmentally Friendly Drilling

COLLABORATIVE EFFORT

Industry – Academia – Government
Environmental Organizations

EFD

SPONSORS

NETL, RPSEA, Mitchell Foundation, Apache, Hess, BP, Chevron, National Academy of Sciences, USAID, Pioneer Natural Resources, Shell, GE, Statoil, Keane, Halliburton, Tenaris, DNV, Huisman, Alcoa, National Oilwell Varco, Newpark Resources

Management Team

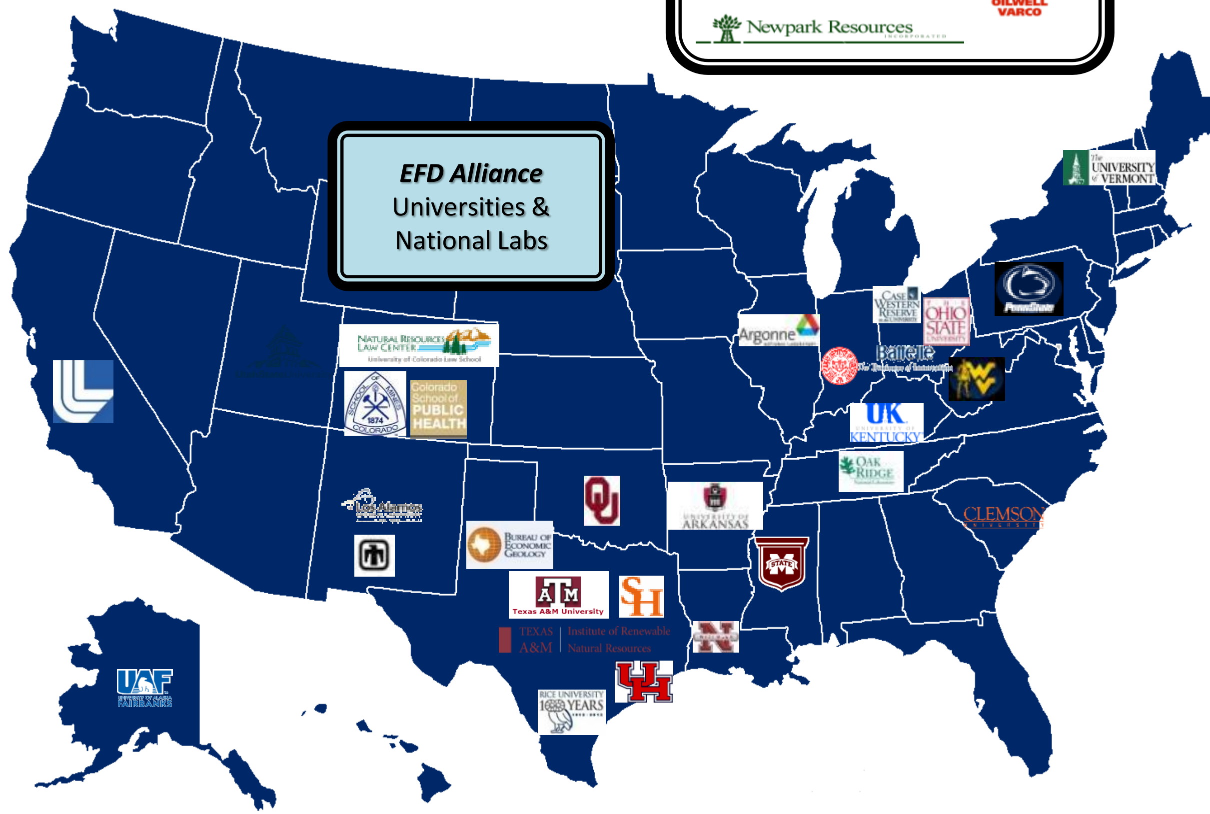
Texas A&M University, LEID LLC, Montan Universität, HARC

ENVIRONMENTAL ORGANIZATIONS

EDF Environmental Defense Fund, The Nature Conservancy, Ducks Unlimited

COLLABORATORS

HART, Groundwater Protection Council, CEA, Gulf of Mexico Alliance, GSI Environmental, American Association of Petroleum Geologists, AACOG, PTTC



HARC

Dual Fuel Diesel Engines

Fracturing

Variable Load

Speed 1500 to 1950 rpm

Drilling

Transient Load Response

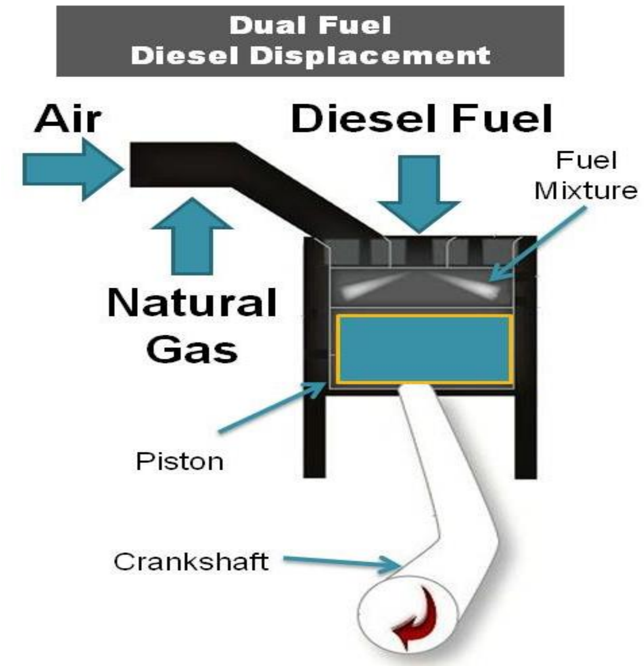
Speed 1200 rpm

Dual Fuel Diesel Engine

Diesel Fuel and Natural Gas Used Together

Fumigation Systems

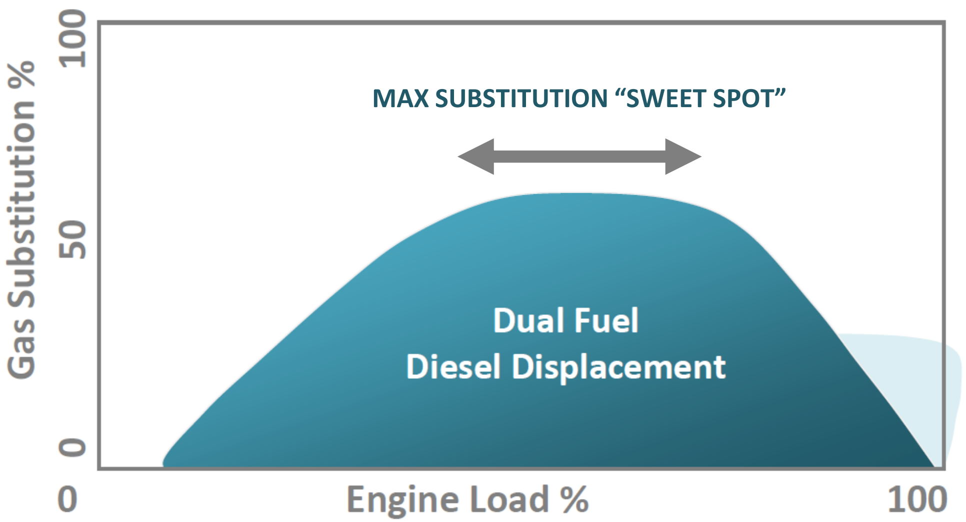
Natural Gas Fuel Introduced Into
Engine Air Intake in Vapor Phase



GRAPHICS ADAPTED FROM
CUMMINS

POWERED BY NATURAL GAS

Replace Diesel Fuel with Gas Fuel



Substitution / Diesel Displacement

Maximum Substitution Occurs in the
Operating Range known as the "Sweet Spot"

Dual Fuel Diesel Savings

Example – 50% Substitution of Diesel Fuel with Natural Gas

Table 1. Example of Dual Fuel Diesel Cost Savings

A rig that consumes 1,500 gallons of diesel fuel per day could save $888,045 annually, $2,433 daily, by substituting natural gas for 50% of the diesel fuel typically used.

Diesel Fuel $3.24 / gallon

EIA Diesel Fuel Price Index, June 23, 2018

https://www.eia.gov/petroleum/gasdiesel/

Diesel Fuel Only			Dual Fuel Substitution 50%				
Gallons	Daily Cost	Annual Cost	Gallons	Daily Cost	Annual Cost	Annual Savings	Daily Savings
1,000	$ 3,244	$ 1,184,060	500	$ 1,622	$ 592,030	$ 592,030	$ 1,622
1,100	$ 3,568	$ 1,302,466	550	$ 1,784	$ 651,233	$ 651,233	$ 1,784
1,200	$ 3,893	$ 1,420,872	600	$ 1,946	$ 710,436	$ 710,436	$ 1,946
1,300	$ 4,217	$ 1,539,278	650	$ 2,109	$ 769,639	$ 769,639	$ 2,109
1,400	$ 4,542	$ 1,657,684	700	$ 2,271	$ 828,842	$ 828,842	$ 2,271
1,500	$ 4,866	$ 1,776,090	750	$ 2,433	$ 888,045	$ 888,045	$ 2,433
1,600	$ 5,190	$ 1,894,496	800	$ 2,595	$ 947,248	$ 947,248	$ 2,595
1,700	$ 5,515	$ 2,012,902	850	$ 2,757	$ 1,006,451	$ 1,006,451	$ 2,757
1,800	$ 5,839	$ 2,131,308	900	$ 2,920	$ 1,065,654	$1,065,654	$ 2,920
1,900	$ 6,164	$ 2,249,714	950	$ 3,082	$ 1,124,857	$ 1,124,857	$ 3,082
2,000	$ 6,488	$ 2,368,120	1000	$ 3,244	$ 1,184,060	$1,184,060	$ 3,244

Rig using 1,500 gallons of Diesel Fuel per day		
Daily Diesel Fuel Cost Savings	$	**2,433**
Annual Diesel Fuel Cost Savings	$	**888,045**

Rig using 2,000 gallons of Diesel Fuel per day		
Daily Diesel Fuel Cost Savings	$	**3,244**
Annual Diesel Fuel Cost Savings	$	**1,184,060**

Please see accompanying Proposal materials for details.

Joint Industry Project

Predictive Model for Dual Fuel Operations

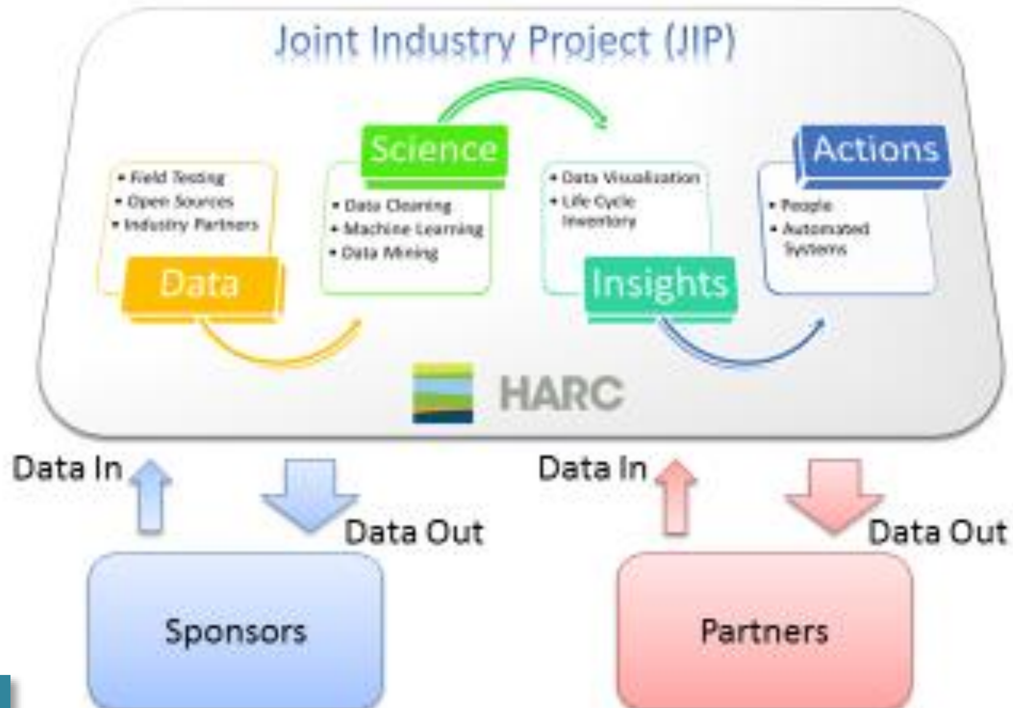
- **Sponsors**

  Seeking up to 12
- **Project Cost**

  Total $185,000

  Divided Among Sponsors
- **Duration**

  6-8 months



CONVERTING DATA
Into Insights for Action

SCOPING
What insights are most meaningful?

PREDICTIVE MODEL
Fuel Consumption, Emissions

LESSONS LEARNED
with Data Science shared with Sponsors

Please see accompanying Proposal materials for details.

Increasing Dual Fuel Diesel Savings

Making the "Sweet Spot" Sweeter

Table 2. Example of Dual Fuel Diesel Cost Savings with Increased Substitution

A rig that consumes 1,500 gallons of diesel fuel per day could realize an incremental savings of $ **177,609** annually by increasing substitution natural gas from 50% to 60%.

Diesel Fuel $3.24 / gallon
EIA Diesel Fuel Price Index, June 23, 2018
https://www.eia.gov/petroleum/gasdiesel/

Diesel Fuel Only			Dual Fuel Substitution					
			50%			60%		
Gallons	Daily Cost	Annual Cost	Gallons	Daily Cost	Annual Cost	Gallons	Daily Cost	Annual Cost
1,000	$ 3,244	$ 1,184,060	500	$ 1,622	$ 592,030	400	$ 1,298	$ 473,624
1,100	$ 3,568	$ 1,302,466	550	$ 1,784	$ 651,233	440	$ 1,427	$ 520,986
1,200	$ 3,893	$ 1,420,872	600	$ 1,946	$ 710,436	480	$ 1,557	$ 568,349
1,300	$ 4,217	$ 1,539,278	650	$ 2,109	$ 769,639	520	$ 1,687	$ 615,711
1,400	$ 4,542	$ 1,657,684	700	$ 2,271	$ 828,842	560	$ 1,817	$ 663,074
1,500	$ 4,866	$ 1,776,090	750	**$ 2,433**	**$ 888,045**	600	**$ 1,946**	**$ 710,436**
1,600	$ 5,190	$ 1,894,496	800	$ 2,595	$ 947,248	640	$ 2,076	$ 757,798
1,700	$ 5,515	$ 2,012,902	850	$ 2,757	$ 1,006,451	680	$ 2,206	$ 805,161
1,800	$ 5,839	$ 2,131,308	900	$ 2,920	$ 1,065,654	720	$ 2,336	$ 852,523
1,900	$ 6,164	$ 2,249,714	950	$ 3,082	$ 1,124,857	760	$ 2,465	$ 899,886
2,000	$ 6,488	$ 2,368,120	1000	**$ 3,244**	**$ 1,184,060**	800	**$ 2,595**	**$ 947,248**

Rig using 2,000 gallons of Diesel Fuel per day		
Daily Incremental Diesel Fuel Cost Savings	**$**	**616**
Annual Incremental Diesel Fuel Cost Savings	**$**	**236,812**

Rig using 1,500 gallons of Diesel Fuel per day		
Daily Incremental Diesel Fuel Cost Savings	**$**	**487**
Annual Incremental Diesel Fuel Cost Savings	**$**	**177,609**

Please see accompanying Proposal materials for details.

Value Proposition

Increasing Diesel Fuel Savings

Please see accompanying Proposal materials for details.

ROI & Payback Period

Project Deliverable:

Predictive Model for Dual Fuel Operations

- Diesel Fuel Consumption
- Gas Substitution
- Engine Emissions

Optimize parameters to increase gas substitution for greater diesel fuel cost savings

Confidently address environmental issues of engine emissions

*NOTE: The ROI and Payback Days calculated here consider only diesel fuel cost savings. This does not include the cost of natural gas fuel, which can vary considerably based upon supply availability, infrastructure, royalties, and other factors. Furthermore, these calculations do not account for the capital cost for dual fuel equipment. When these factors are considered, actual ROI would be reduced, and the number of Payback Days would increase.

Table 3. Sponsor ROI & Payback in Days *

Based on the Example in **Table 2**

A rig that consumes 1,500 gallons of diesel fuel per day could save **$177,609** annually by increasing natural gas substitution from 50% to 60% of the diesel fuel typically used, for daily savings of **$488.**

Return on Investment

Annual Fuel Savings **$177,609/Sponsorship Fee**

Payback in Operating Days

Daily Savings of $488/Sponsorship Fee

Number Sponsors	Sponsorship Fee	ROI	Payback Days
1	$185,000	96%	380
2	$ 92,500	192%	190
3	$ 61,667	288%	127
4	$ 46,250	384%	95
5	$ 37,000	480%	76
6	$ 30,833	576%	63
7	$ 26,429	672%	54
8	$ 23,125	768%	48
9	$ 20,556	864%	42
10	$ 18,500	960%	38
11	$ 16,818	1056%	35
12	$ 15,417	1152%	32

Life Cycle Inventory (LCI)

- Emissions
- Fuel Supply & Consumption
    - Diesel Fuel, Natural Gas Fuel
- Operational Parameters
    - Anticipated Engine Loads
- Locational Factors
- Uncertainty

Predictive Model

- Dual Fuel Technology
  - Predict Fuel Costs & Emissions
  - Key Data for Life Cycle Assessment
- Data Flow In
  - Open Sources, Industry Partners
- Data Flow Out
  - Prediction: Broaden Scenarios

Applied Data Science

Data Cleaning

- Determine Applicable Features
- Purge “Bad” Data
- Harmonize definitions and methods
- Format data, ready-for-modeling

Cleaning → Analysis → Visualizations → Deliverables

Applied Data Science

Data Analysis

- Preliminary data exploration
- Machine learning tool box
  - regression, classification
- Build model to **predict**
  - Fuel savings, operations and emissions
  - Key data for life cycle assessment

Data Visualization

- Predicted data and accuracy
- Correlation matrix, histogram, boxplot
- No raw (site-specific) data shared

Deliverables

- **Predictive Model Output**
  - Visualized Data and Predictions
  - Diesel & Natural Gas Fuel Consumption & Substitution Ratio
  - Engine Emissions
- **Life Cycle Assessment** (if necessary)
- **Interactive Online User Interface**

Data Exploration

Features (Steady State)

- Activity: hydraulic fracturing (HF) or drilling (DR)
- Engine make and model
- After-treatment system (ATS): e.g. DOC, SCR
- RPM, power, NG heating value, loading
- Fuel consumption (diesel, NG)
- Fuel efficiency, displaced diesel, substitution ratio
- Emissions (GHG, NMHC+NOx, CO and methane)

Feature List Example

Feature	Unit	Data Type	Calculation and method
Source	N/A	String	Origin of data
AverageYN	N/A	Category	Y-this is the averarge of several observations; N-this is a single and independent observation
Activity	N/A	Category	HF-hydraulic fracturing; DR-drilling
Engine_make	N/A	String	The manufacturer of the engine
Engine_model	N/A	String	The model of the engine
Rated_speed_rpm	RPM	Numeric	The rated speed of the engine
Rated_power_kw	kW	Numeric	Power output at 100% loading
Power_kw	kW	Numeric	Actual power output during operation
NG_LHV_btupercf	Btu/cf	Numeric	lower heating value of NG used
Fuel_consump_DLEperkwh	DLE/kWh	Numeric	Total fuel consumption in diesel liter equivalent (DLE) – convert to diesel gallon equivalent (DGE)
Diesel_consump_DLEperkwh	DLE/kWh	Numeric	Total diesel consumption in diesel liter equivalent (DLE) – convert to diesel gallon equivalent (DGE)
NG_consump_DLEperkwh	DLE/kWh	Numeric	Total NG consumption in diesel liter equivalent (DLE), including converted and loss – convert to diesel gallon equivalent (DGE)
Engine_load	1	Numeric	Engine load(s) during the operation
Fuel_efficiency_ZECE	1	Numeric	power out / (NG power in - CH_4 loss + diesel power in)
Diesel_disp	1	Numeric	1-DF diesel rate/DO diesel rate
Substitution_ratio_corrected	1	Numeric	(NG power in - CH_4 loss) / Total Fuel in
Substitution_ratio_industry	1	Numeric	NG power in / Total Fuel in
Methane_loss	1	Numeric	Methane out / Methane in (Non-Combusted Methane (NCM) aka "methane slip")
ATS	N/A	Category	Aftertreatment system, Y-emissions after ATS; N-emissions before ATS or ATS is not applied
Emission_GHG	CO_2e kg/kWh	Numeric	GHG emission includes CO_2, CH_4 (GWP=25) and N_2O (GWP=298)
Emission_NMHC_NOx	g/kWh	Numeric	NMHC emissions + NO_x emissions
Emission_CO	g/kWh	Numeric	CO emission

Supervised Learning

- Linear Regression "supervised learning"
- Selected features
- Randomly split 80% data for modeling, 20% for testing
- 1,000 random scores (neural regression 100 random scores)
- MARE: Mean Absolute Relative Error
  - e.g. a ± b%

$$MARE = \frac{\sum \left| \frac{Predicted\ value\ - Test\ value}{Test\ value} \right|}{Number\ of\ test\ value}$$

- RMSE: Root Mean Squared Error
  - e.g. a ± c

$$RMSE = \sqrt{\frac{\sum (Predicted\ value\ - Test\ value)^2}{Number\ of\ test\ value}}$$

Prediction Summary Example

Parameters	Unit	Representative Value*	Best Prediction MARE**	Best Prediction RMSE***
Fuel efficiency	1	0.266	**4.3%**	0.015
Diesel displacement	1	0.604	**7.2%**	0.055
Substitution ratio	1	0.698	**4.8%**	0.044
GHG emission	CO2e kg/kWh	1.880	**3.9%**	0.095
NMHC+NOx w/o ATS	g/kWh	10.194	**10.4%**	1.15
NMHC+NOx w/ ATS	g/kWh	5.123	**10.4%**	0.61
CO w/o ATS	g/kWh	23.65	**4.8%**	1.36
CO w/ ATS	g/kWh	0.217	**21.4%**	0.063

*Mean value in database
**MARE: Mean Absolute Relative Error
***RMSE: Root Mean Squared Error

Application Scenarios

- **Optimized**
  - Best accuracy

Optimized features → Model based on optimized features → Prediction

- **Customized**
  - Best practice

Customized features → Model based on customized features → Prediction

Application Scenarios

How to use data in LCA (example)

- LCA Software
  - Processes
  - Energy
  - Fuels
- Carbon Footprint

Life Cycle Inventory

Output (function unit):
1 kWh electricity by dual fuel

Input:
NG at production onshore, diesel, infrastructure

Emissions:
GHG, NMHC+NOx, CO

Description:
Emissions are predicted by activity, RPM, loading, NG and diesel consumption, etc.

Additionally…

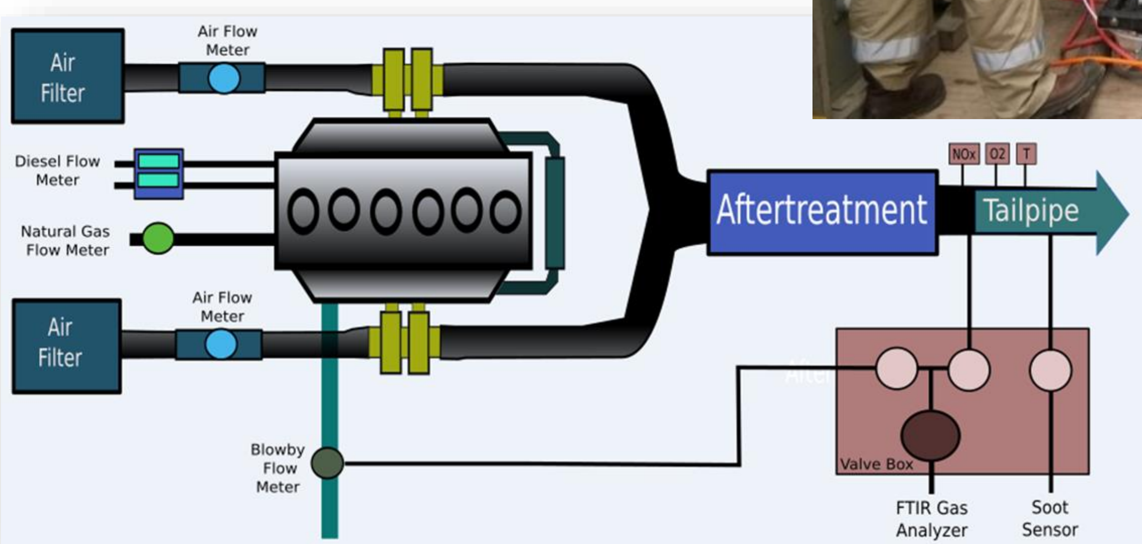
Prediction is a powerful tool, but still involves some uncertainties… not a substitute for field testing, data collection & analysis

EFD

iBox

Intrinsically Safe Instrumentation

iBox



Data Acquisition & Control System

- LabVIEW FPGA
  - Design & developed at HARC
- Records data for fuel flow, air flow, temperatures, pressures, ambient conditions, gaseous emissions & soot

Dual Fuel Study Parameters

Gaseous Emissions, Soot, Fuel Consumption, Engine Operation Conditions

Gaseous Emissions	
Nitrogen Oxide	Ethylene
Nitrogen Dioxide	Acetylene
Nitrous Oxide	Propane
Ammonia	Propylene
Water	Diesel
Carbon Monoxide	Formaldehyde
Carbon Dioxide	Acetaldehyde
Methane	Formic Acid
Ethane	Methanol

Ambient Conditions	
Temperature (C)	Pressure (mbar)
Humidity (%)	Dew Point (C)

Exhaust Conditions	
Temperature (C)	Soot
Oxygen	A/F ratio

Fuels
Fuel supply Flow
Fuel Return Flow
Diesel Fuel Consumption
Natural Gas Flow

Measurements

- CO
- NO, NO_2 (NO_x)
- VOCs (including formaldehyde [CH_2O])
- Soot (indicative of PM)
- Non-Combusted Methane (NCM) aka “slip”
- Direct Measurement of Diesel Fuel and Natural Gas Fuel

Thank You

HARCresearch.org

HARC (härk), *n.*
an independent research
hub helping people thrive
and nature flourish.