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IADC®

PROPOSAL FOR A JOINT INDUSTRY PROJECT

APPLY DATA SCIENCE FOR RAPID MODELING OF DUAL FUEL DIESEL ENGINE TECHNOLOGY

Environmentally Friendly Drilling

EFD

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HOUSTON ADVANCED RESEARCH CENTER
8801 Gosling Road | The Woodlands, TX 77381
T 281-364-6000 | F 281-364-6001 | www.HARCresearch.org

Environmentally Friendly Drilling

Executive Summary

Proposed Joint Industry Project

Apply Data Science for Rapid Modeling of Dual Fuel Diesel Engine Technology

The Houston Advanced Research Center (HARC) Environmentally Friendly Drilling Systems Program (EFD) seeks industry support for a proposed Joint Industry Project (JIP) to develop a predictive model using Data Science. ***The model will support planning and optimization of operations by addressing uncertainties of fuel consumption, engine performance, emissions, and environmental factors.*** An important objective of the proposed Project is to optimize substitution of natural gas fuel for diesel fuel to ***realize value by increasing diesel fuel savings***.

HARC EFD is seeking Sponsorship from operating companies, drilling contractors, service providers, and other industry stakeholders to support this Project with guidance, technical input, and funding. The project will take 6-8 months to complete at a cost of $185,000 to be divided among up to 12 Sponsors – the more Sponsors participating, the lower the cost to each. ***If 12 Sponsors join the cost to each would be $185,000 /12 = $15,417.*** With significant potential benefit in diesel fuel cost savings Sponsors could realize a rapid Return on Investment (ROI), as described in the full Proposal sections on "Cost" and "Cost per Participant" (page 10) in which "Table 3 Sponsor ROI & Payback" can be found.

Table 3. Sponsor ROI & Payback in Days *

Based on the Example in **Figure 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 (ROI)

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
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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

***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.**

Contact

Carolyn LaFleur, P.E.

Research Scientist, Energy & Sustainability

Houston Advanced Research Center

8801 Gosling Road

The Woodlands, Texas 77381

clafleur@harcresearch.org

office 281.364.6047

mobile & text 281.703.8170

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www.harcresearch.org

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Introduction

Hydraulic fracturing, directional drilling and other advanced technologies have enabled production of domestic oil and gas from shale and tight rock throughout North America. This new age of petroleum brings with it new challenges, to integrate technological advancements, protect the environment, and engage communities, all while operating in challenging economic circumstances. The sections that follow are organized according to the format of the IADC online submission form.

Environmentally Friendly Drilling

The HARC Environmentally Friendly Drilling (EFD) Program provides unbiased science to address the environmental and societal aspects of all oil and gas activities. Research focuses on water resources and treatment technologies, flaring mitigation, air quality, engine emissions and more. EFD works collaboratively with partners in industry, academia, environmental groups, and regulatory authorities, engaging diverse perspectives to define challenges and develop solutions. The EFD Program has performed research in technologies and practices to improve environmental performance, including field research to better understand challenges, test new ideas and document results.

The EFD Alliance is comprised of research institutions through the US and abroad, working together to leverage the best scientific resources in partnerships formed for the tasks at hand. The EFD Industry Consortium is made up of oil and gas operating companies, oilfield service companies, purveyors of technology, and other private business entities. Environmental groups and regulatory authorities have an important voice in the collaborative process that guides the research.

With a proven track record of accomplishments in a diverse disciplines, the EFD program is engaged in efforts to address the most pressing concerns of the energy industry, the public, regulators, and other stakeholders. Current efforts focus on carbon emissions, water management, and in-depth analyses of technologies that offer environmental and economic advantages with Life Cycle Assessment (LCA). Joining with researchers from across the country, EFD is investigating fugitive methane, clean power, and the practices and technologies that offer alternatives to underground injection for produced water management. This research is driven by need, and funded from various sources including government grants, foundations and industry interests. EFD has established a reputation for prioritizing science, not political or advocacy pressures. These accomplishments include programs in workforce development, coastal ecology, technology integration, field trials, and more.

Dual Fuel Diesel Engines

A dual fuel engine is a diesel engine that has been adapted to utilize natural gas fuel along with diesel fuel, co-combusted simultaneously. Using natural gas fuel reduces the amount of diesel fuel required. In most dual fuel engines, natural gas fuel in vapor phase is injected into the engine air intake. The gas fuel is blended with air and supplied to the engine. The engine can operate with the addition of gas fuel (dual fuel mode) or on diesel fuel alone (diesel-only mode). In addition to dual fuel engine packages of Original Equipment Manufacturers (OEM), most diesel engines can be modified to utilize natural gas with the addition of an aftermarket kit.

Dual Fuel significantly reduces diesel fuel consumption and offers certain environmental benefits. Fuel consumption and emissions can vary greatly depending on gas composition, how the engine is operated, and other factors. Dual fuel engines can displace approximately 40% - 70% of typical diesel fuel consumption over a range of operating conditions.

Importantly, the substitution ratio typically calculated on the basis of the energy content of the two fuels is similar, but not the same as amount of diesel displaced. That is, the actual amount of diesel fuel displaced is somewhat less than indicated by the "substitution ratio". This is due to the fact that some amount of gas supplied to the engine as fuel is not burned, but passes through the engine and is emitted in exhaust. This **Non-Combusted Methane (NCM) aka "methane slip"** bears directly on actual fuel economy attained with the use of dual fuel, as well as greenhouse gas emissions.

Data Science (e.g. machine learning) is applied to analyze field testing data and laboratory studies of dual fuel engines enabling rapid prediction of emissions, fuel consumption and other parameters to optimize operation of dual fuel engines. The model is integrated into a LCA to evaluate economic and environmental aspects for a range of operating conditions. *Predictions enable optimization of parameters to increase diesel displacement and engine operating conditions for greater fuel cost savings.*

Technical Area

Advances in dual fuel technology used in oilfield operations such as drilling and hydraulic fracturing offer opportunities to reduce fuel usage, costs and emissions. As such, this Project will focus on drilling and completions, in the realm of **"Production"**.

Sponsors

EFD has enjoyed the support of operating companies and service providers as Program Sponsors in previous research efforts. In addition to funding, Sponsors provide insights on areas of research need. The proposed Project is a direct outgrowth of these collaborations in which scientists have studied dual fuel engines in the field. EFD will engage industry partners for this Project to provide funding support as well as guidance on critical parameters of operational value. EFD is seeking up to 12 Sponsors to participate in this effort, sharing the Project cost of $185,000 equally between them. Additional details are provided in the "Cost per Participant" section of this document.

Title

"**Apply Data Science for Rapid Modeling of Dual Fuel Diesel Engine Technology**"

Submitted

Houston Advanced Research Center (HARC) Environmentally Friendly Drilling Program (EFD) respectfully submits this proposal for a Joint Industry Project (JIP, the Project). Led by Dr. Richard Haut, Director, EFD has a distinguished history of industry collaboration, providing unbiased science to address environmental aspects of oil and gas operations.

Principal Investigators

This Project will be led by Carolyn LaFleur, P.E., Research Scientist, in collaboration with Dr. Fanxu Meng, P.E., Research Associate. Other HARC researchers and staff will support this Project as needed, including Information Technology (IT) support in development of models and online prediction tools for users.

Carolyn LaFleur holds a B.S. and M.Eng. in Civil Engineering from McNeese State University in Lake Charles, Louisiana, and is a registered Professional Engineer in Minnesota and Texas. In addition to engineering consulting, she has worked in the offshore oil and gas industry, land surveying, and petrochemical manufacturing. Her work with EFD focuses on the study, development and testing of innovative technologies that reduce the environmental impact of oil and gas activities. Carolyn is also involved in regional and nationwide initiatives to integrate sustainability and resilience in built environments.

Fanxu "Fan" Meng holds a Ph.D. in Chemical Engineering from Texas A&M University, where he studied real-time monitoring and characterization of nanoparticles and chemicals via microfluidics. Dr. Meng obtained his B.S. and M.S. in Chemical Engineering from Tianjin University. He is a Professional Engineer (PE) licensed in the State of Texas and a certified Project Management Professional (PMP). He is also certified in Microsoft Professional Program-Data Science. Fanxu works with the EFD program on dual fuel research, including field testing to measure emissions and fuel consumption, and laboratory study of novel catalyst formulations to treat dual fuel exhaust emissions. Fanxu also works with clean energy initiatives at HARC, providing technical assistance for implementation of Combined Heat and Power (CHP) Projects.

Business Impact

Modern diesel-powered rigs and fracturing pumps are fitted with dual fuel diesel engines or with engines that can be retrofit to function in dual fuel mode. As such, dual fuel represents a pervasive technology to power drilling and fracturing. Dual fuel engines can substitute as much as 70% natural gas for the diesel fuel typically used. Given the potential for volatility in diesel fuel prices and annual fuel costs into the millions the prospect of replacing diesel fuel with less costly natural gas fuel has great appeal.

Table 1 below illustrates the magnitude of potential diesel fuel savings based upon a simple averaged substitution rate of 50%. Using a diesel fuel price of $3.24 per gallon (from EIA Diesel Fuel Price Index, June 23, 2018) a rig that consumes 1,500 gallons of diesel fuel per day could potentially save $888,045 annually by substituting 50% of diesel fuel with natural gas.

Importantly, this example considers only a generalized, average substitution rate to illustrate diesel fuel savings. Actual total fuel costs must also include the cost of natural gas fuel, supplied by field gas, Compressed Natural Gas (CNG), or Liquefied Natural Gas (LNG). Myriad factors affect the cost of delivering natural gas to the site, such as local availability, transport cost, field gas fueling infrastructure, royalties, and so on.

Diesel fuel consumption and potential savings with dual fuel can readily be predicted with the proposed mode. Maximizing substitution throughout the duty cycle is the key to getting the greatest economic benefit from the investment in dual fuel technology. In our studies we have found that with optimal conditions diesel fuel savings can be significantly increased (up to 12% at the low end of the substitution spectrum). Data Science will be used to develop a model for planning and optimizing operating parameters for fuel economy and other aspects.

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**

Technical Objectives

By converting data into insights for action, Data Science can be applied to reduce cost and improve safety, efficiency, and sustainability. In this vanguard effort, HARC will utilize Data Science in a Life Cycle Assessment (LCA) of dual fuel diesel engine technology. LCA offers an innovative approach to analyzing a multitude of economic and environmental aspects in a predictive framework for decision support.

In addition to predictions on fuels and engine parameters, the model will also provide predictions on engine emissions. Information of this type enables operating companies, drilling contractors, and service providers to confidently address questions on critical aspects of environmental performance involving air quality and fuel truck traffic. These issues are of great importance for communities in which there is intensive development activity. *In some instances these key environmental aspects can restrict how, when and where drilling and hydraulic fracturing can occur.*

Major elements of the Project will include:

- Gathering data from field testing, public open sources, and industry partners, to include representation of regional and technological variability
- Applying Data Science to harmonize data, fill data gaps and assure high-quality and unbiased prediction
- Modeling and visualization to extract insights and actionable information concerning the use of dual fuel technology

An important objective of this work is to provide a coherent framework for improving overall natural gas substitution. This requires determining those conditions in which substitution is maximized and adjusting operations accordingly. The objective is to attain a higher average rate of natural gas substitution throughout the engine duty cycle.

Sustained incremental increases in substitution directly result in diesel fuel savings. The example in **Table 2** on the next page illustrates the effect of boosting overall average substitution by 10%, from 50% to 60%.

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**

Methodology

Life Cycle Assessment (LCA) can be utilized to evaluate economic and environmental factors for a range of operating conditions from a holistic perspective. Life Cycle Inventory (LCI) is the basic unit for assembly of LCA. An LCI usually contains the function unit, input energy and material, and output materials and emissions, etc. For dual fuel technology, emissions are related to operational parameters such as engine loading, rpm, fuel consumption and exhaust After-Treatment System (ATS, if applicable). Data Science can estimate the uncertainty of the LCI among different data sources. Identifying patterns with Data Science tools such as machine learning helps to estimate the uncertainty.

Sponsor Engagement

Project sponsors will gather at HARC to kick off the Project and discuss important issues, objectives, and scoping priorities. This insight and guidance are needed to assure that Project Sponsor needs are addressed the key Project deliverable, the predictive model. This meeting will be limited to Sponsors only, with predetermined rules of engagement for participants.

HARC proposes to visit selected Sponsors' field locations (drilling and fracturing) in Texas for first-hand observations to better understand operational aspects pertaining to development of the model. HARC personnel have completed SafeLand safety training for onshore operations, have full Personnel Protective Equipment, and will strictly adhere to all site safety requirements.

Predictive Modelling

HARC scientists have established proof of this concept with a number of observations from field and laboratory studies. Each observation contains specific characteristics of a dual fuel engine and its emissions at specific operating conditions.

After data cleaning and descriptive analytics, correlations are found between engine operational characteristics, fuel consumption, and emissions. A regression model is created to predict emissions of a dual fuel engine from its features. In proof of concept, results and respective scores from 1,000 repeated random experiments are analyzed. The scores include Mean Absolute Relative Error (MARE) and Root Mean Squared Error (RMSE). The average relative errors between predicted values and actual values mostly range from 3.9% to 10.4%. From this was built a framework for the predictive model for LCI.

- Activity: hydraulic fracturing (HF) or drilling (DR)
- Engine make and model, features
- After-Treatment System (ATS):
  - e.g. Diesel Oxidation Catalyst (DOC), Selective Catalytic Reduction (SCR)
- Operating Factors
  - Engine Speed (RPM)
  - Power/Horsepower/Torque (kWh/BHP/lb-ft)
  - Fuel Composition / Natural Gas Heating Value (Btu/scf)
  - Engine Loading (%)
  - Fuel Consumption (diesel & natural gas)
  - Fuel Efficiency, Displaced Diesel, Substitution Ratio

- Emissions
  - Greenhouse Gas (GHG)
  - Non-Methane Hydrocarbon + Nitrogen Oxides ($NMHC+NO_x$)
  - Carbon Monoxide (CO)
  - Non-Combusted Methane, aka “Methane Slip” ($NCM,CH_{4,}$)
  - Soot (mass concentration, indicative of Particulate Matter (PM), does not distinguish particle size)

Deliverables

The key Project deliverable is a predictive model for dual fuel operations. The model will be hosted with HARC resources, and made available to Sponsors with a password-protected online user interface. Configuration details for the predictive model features and user interface will be driven by Sponsor input.

Startup Date

As no special equipment or facilities are required for this Project the Project can commence whenever sufficient sponsorship is attained. This could occur by as August or September this year. The effort would begin with a kick-off meeting and workshop for the purpose of identifying key issues and outcomes expected. This important scoping exercise is necessary to assure that Sponsor expectations are met.

Project Duration

This Project can be completed in 6-8 months.

Project Cost

Total cost for this effort is projected at $185,000, to be shared among up to 12 Sponsors. This would include all personnel costs. The proposed Project cost also includes limited travel to field locations to observe operations and better understand key issues of importance for Sponsors.

Cost per Participant

EFD is seeking up to 12 Sponsors to participate HARC EFD is seeking Sponsorship from operating companies, drilling contractors, service providers, and other industry stakeholders to support this Project with guidance, technical input, and funding. The project will cost $185,000 to be divided among up to 12 Sponsors – the more Sponsors participating, the lower the cost to each. ***If 12 sponsors are secured, the cost to each would be $185,000 /12 = $15,417.*** With great potential benefit in diesel fuel cost savings Sponsors would realize a rapid Return on Investment (ROI) as illustrated in **Table 3.**

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

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Daily Savings of $488/Sponsorship Fee

Number Sponsors	Sponsorship Fee	ROI	Payback Days
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Comments

Natural Gas Fueling

Although the scope of this Project does not encompass an examination of the various types of natural gas fueling options, this is an important factor when considering total fuel costs. ***To characterize the many possible configurations of natural gas fueling infrastructure and supply in a meaningful way would require exhaustive study, not considered in the scope of this Project.*** However, such information would be very valuable in terms of capturing better information on costs associated with natural gas fueling. Such a study could constitute a future phase of work that would build upon this Project.

Transient Load Conditions

The engine operating parameters considered for this Project would reflect steady state conditions, and would not account for transient loading. Indeed this information would be of great interest, but is not considered in the scope of this Project. ***To characterize the many aspects of transient loading in a meaningful way would require exhaustive study, not considered in the scope of this Project.*** Such a study could constitute a future phase of work.

Engine Testing

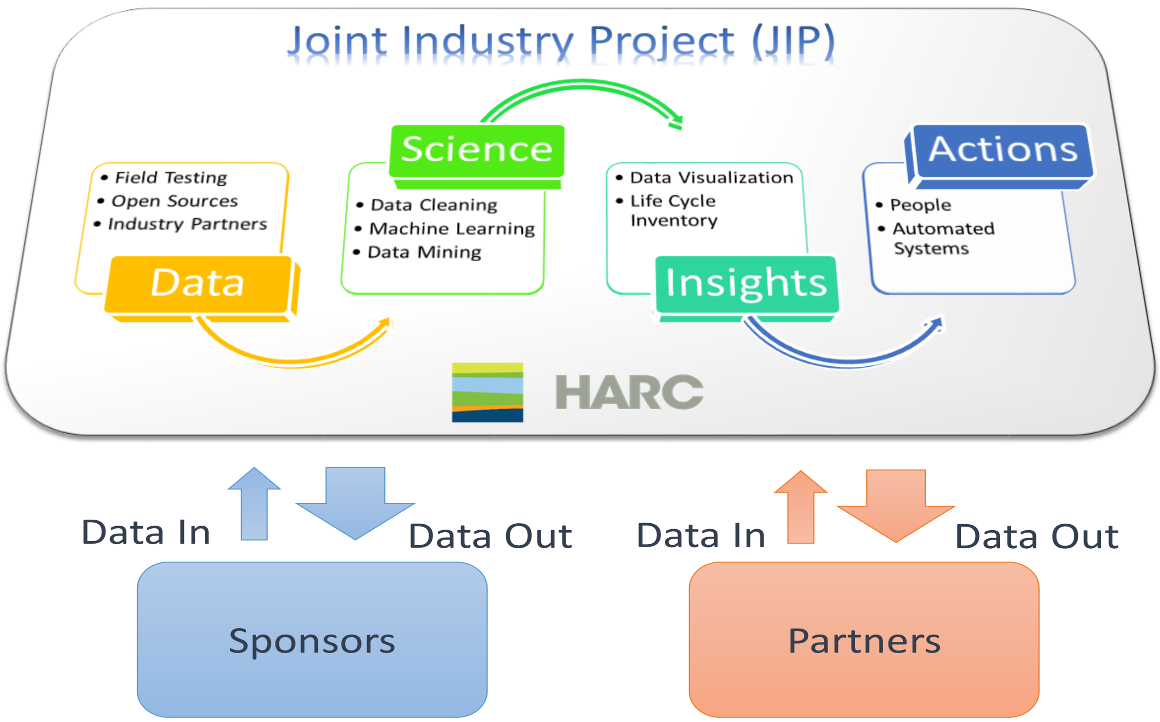
HARC recognizes the power of predictive modeling to inform planning and optimization endeavors. Advances in Data Science provide an understanding of uncertainties in the use of data, though some uncertainties still exist. ***Predictions are not a substitute for direct measurement of these key operating parameters, including fuel consumption and emissions.*** HARC has developed specialized, intrinsically safe instrumentation enabling such measurements to be made at an active drilling or fracturing operation. Field testing of this type is beyond the scope of this proposed Project, but is available to Sponsors who wish to avail themselves of this service for an additional fee.

Melding Experience & Data Science

The "New Age in Drilling" presents tremendous opportunity to exploit the many advantages that can be realized with Data Science. Melding Data Science with the collective wealth of historical experience and wisdom of the drilling industry will lead to advances that will amaze both data scientist and seasoned drilling hands. As with all human endeavor, adaptation is the key to success, and even survival. This is the challenge, to bring together the best of both worlds for the benefit of all.

Life Cycle Assessment

Data Science Performance Prediction
Dual Fuel Diesel Engines



Contact

Carolyn LaFleur, P.E.
Research Scientist, Energy & Sustainability
Houston Advanced Research Center
8801 Gosling Road
The Woodlands, Texas 77381
clafleur@harcresearch.org
office 281.364.6047
mobile & text 281.703.8170

> *"It would be an honor and privilege to work with the distinguished membership of the IADC in this important endeavor."*

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