Pacific Northwest
NATIONAL LABORATORY

PNNL-37083

Transport Affordable Clean Hydrogen Energy via Existing Pipeline Infrastructure (CRADA 573)

September 2022

Nathan Prisco
Carlos A. Fernandez

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Cooperative Research and Development Agreement (CRADA) Final Report

Report Date:

In accordance with Requirements set forth in the terms of the CRADA, this document is the CRADA Final Report, including a list of Subject Inventions, to be provided to PNNL Information Release who will forward to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research. **PNNL acknowledges that the CRADA parties have been involved in the preparation of the report or reviewed the report.**

Parties to the Agreement: Mighty Pipeline and PNNL

CRADA number: 573

CRADA Title: Transport Affordable Clean Hydrogen Energy via Existing Pipeline Infrastructure

Responsible Technical Contact at DOE Lab(PNNL): Carlos A. Fernandez

Name and Email Address of POC at Partner Company(ies): Nathan Prisco, nathan.prisco@mightypipeline.com

Sponsoring DOE Program Office(s): Arctic Advanced Manufacturing Program (DESC0014664)

Joint Work Statement Funding Table showing DOE funding commitment:

	Funding Amounts			
CRADA Parties	**DOE Funding**	**Funds-In**	***In-kind**	**Total**
PNNL and Mighty Pipeline	$37,901.00		$36,250.00	
DOE Funding to PNNL		$37,901.00	N/A	

Total of all Contributions				

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

Presentations:
1. Presentation to Japan's Strategic Innovation Program "energy-carriers" 2021
2. Presentation to Fueltech Solutions AS based in Trondheim, Norway 2021
3. Presentation to Mechanical Solutions, INC based in Whippany, New York 2021
4. Presentation to CleanTech Alliance Conference 2022

Patent applications:
WO2023137304A2
WO2023137304A3

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

Patent applications:
WO2023137304A2
WO2023137304A3

Trademark: MightySolution™

Executive Summary of CRADA Work

Our Nation's vast network of oil pipelines span over 230,000 miles connecting remote energy producing regions to distant markets. The COVID-19 pandemic's influence on oil prices intensified technical and economic vulnerabilities afflicting the Trans-Alaska Pipeline System (TAPS, operating below 25% capacity) that may soon resurface as energy demand shifts to low carbon sources. Through the opportunity afforded by the Arctic Advanced Manufacturing Program, I've toured the great State of Alaska learning about its culture, unique energy challenges, business ecosystem, research institutions, and regulatory agencies. With encouragement and support from dedicated Alaskans and my professional mentors, I've founded Mighty Pipeline for the purpose of developing and commercializing proprietary technology and hardware to convert oil pipelines into clean hydrogen energy transmission systems. Leveraging the advanced technical capabilities of Pacific Northwest National Laboratory, we've demonstrated proof-of-concept (TRL = 3) and are seeking pre-pilot development project opportunities to conduct hardware and system level tests. If we successfully achieve technical and regulatory milestones, Mighty Pipeline's technology could be available to help facilitate bulk clean hydrogen energy export this decade.

Summary of Research Results

This product contains Protected CRADA Information, which was produced on [2021-2023] under CRADA No. 573 and is not to be further disclosed for a period of five (5) years from the date it was produced except as expressly provided for in the CRADA.

Introduction

Mighty Pipeline was founded with the belief that our generation will forever be judged by how quickly and efficiently we can produce and deliver affordable clean hydrogen energy at scale. Today, even in regions where clean hydrogen can be affordably produced, it is not typically accessible to energy consumers. Part of hydrogen's grand challenge is that it relies on costly transportation and storage infrastructure, delivery costs alone can range from \$0.25 to more than \$6/kg H_2 depending on factors such as distance, transmission method, volume, and end-use needs. Lowering hydrogen delivery prices will help to promote an equitable energy transition, achieve global emissions reductions, and enhance US manufacturing competitiveness. Where possible, reconfiguring existing fossil supply chains for hydrogen distribution can reduce hydrogen delivery prices by more than 50%.[1] One pathway is MightySolution™, a 1st of a kind fuel emulsion

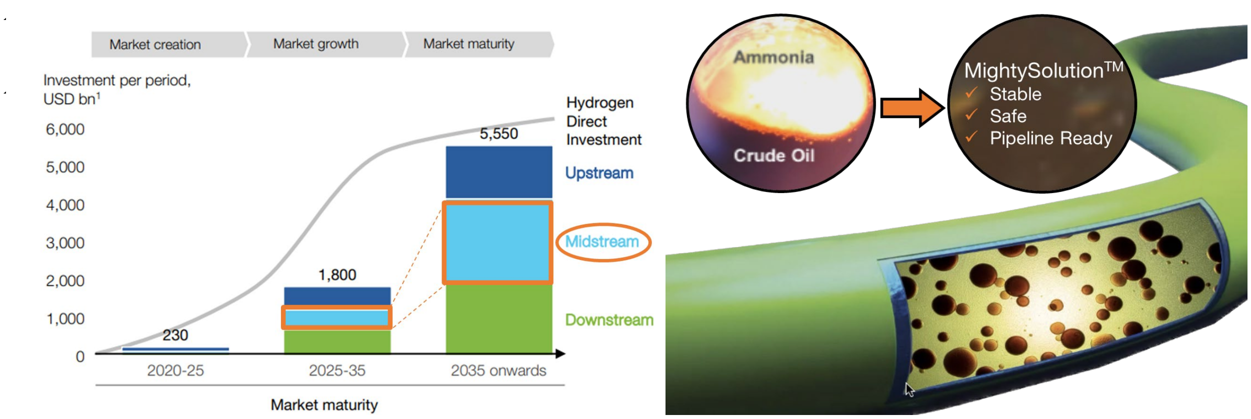
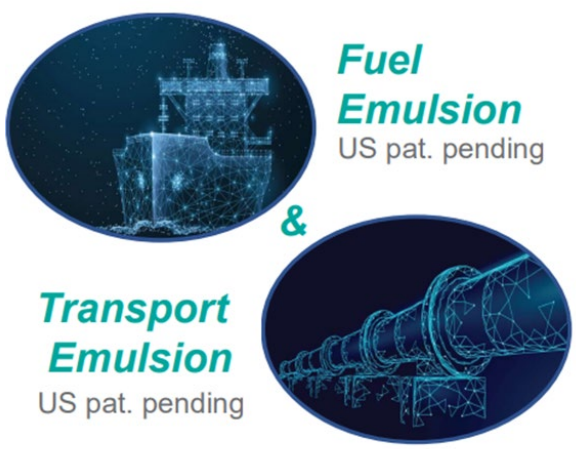


Figure 1) (Left) Hydrogen Council policy recommendation for hydrogen and ammonia investments, midstream energy sector (transportation, distribution, storage) including pipelines to comprise over 1/3rd of total investments.[15] (Right) Clean ammonia blending into oil pipelines with emulsion technology, advantages include higher pipeline ROI (from volumetric capacity enhancement & new revenue generation) and low-cost, efficient clean ammonia recovery enabled at pipeline terminus.

Description of the Research Project

The work effort comprised a two-year fellowship between the University of Alaska Fairbanks and Pacific Northwest National Laboratory (PNNL) with the goal of advancing an early-stage clean energy manufacturing concept into a commercial product or manufacturing business. Clean ammonia (NH_3) is now widely considered as part of a clean hydrogen energy economy. It can be manufactured using renewable electricity ("green") or fossil resources with carbon mitigation ("blue").[2], [3] Mighty Pipeline's technology can improve safety and cost-effectiveness of clean ammonia transportation, storage, or fuel use. Our product:



Fuel Emulsion**)** Clean heavy fuel blends for boilers, engines, and turbines deliverable at less than $2/gallon gasoline equivalent at scale.

Transport Emulsion**)** grants oil pipelines the ability to transport clean hydrogen energy in the form of ammonia. Emulsion form can increase pipeline's max capacity, generate value upon separation, and improve pipeline safety of ammonia. This could help jumpstart a clean hydrogen manufacturing economy in the State of Alaska assuming technical and regulatory milestones are met.

Fairbanks, Alaska — About 30% of program time was spent physically near the University of Alaska (COVID-19 restrictions). Customer discovery interviews were conducted either virtually or in-person with stakeholders from Alaska's rural and central power utilities, petroleum and mining industries, and business ecosystem. To summarize:

- Transportation makes up to 50% or more of the cost of typical commodities in Alaska, most all commodities are imported.
- Alaska's utilities generally are not amenable to trialing new fuel technology unless funds are provided for end-of-life removal (prior projects have become a major liability).
- Since 1988, declining oil productivity has inevitably meant less total revenue and higher operating costs per barrel in Alaska's petroleum industry (below 25% peak capacity).

- Alaska's petroleum industry has become increasingly lean over the years (a potential opportunity for a hard-tech startup to deliver low-carbon innovation).
- MightySolution™ has attracted clean energy developer interest as a prospective way to link "landlocked" clean energy production sites to distant markets using oil pipelines.
- Mass market ammonia combustion boilers, engines, and turbines could improve prospect of fuel ammonia use in Alaska in conjunction with our fuel emulsion technology by 2025.

Richland, Washington — About 70% of physical program time was budgeted to be spent on development milestones. As an overarching technical goal, the fuel emulsion should be capable of being stored as a fuel but also capable of being easily broken to recover clean ammonia for individual sale as a carbon-free commodity. The technical project goals were:

M1) Recalibrate available PNNL equipment to produce a fuel emulsion product.
M2) Validate that a fuel emulsion can be produced with sufficient shelf life for long-distance pipeline transport and/or long-term storage as a fuel commodity.
M3) Perform rheological testing of fuel emulsion for purpose of informing process equipment selection and simulating pipeline performance / safety design features.
M4) Develop a technical economic framework to assess hydrogen delivery option. (*ongoing*)

The partner lab at PNNL contributed advanced technical expertise and capabilities that few other DOE laboratories possess allowing for the testing of ammonia-based energy fluids under realistic conditions, see Fig. 2 for systems and data overview. M1) was achieved allowing for rheological testing and direct observation of mixing/unmixing processes. M2) Emulsion stability under flow conditions (*i.e.*, pipeline transport) typically far exceeds storage stability (*i.e.*, fuel tank) but requires flow-loop testing to ascertain. Good storage stability (static) was observed below 0 ºC, this is attributable to the selected stabilizer's properties but aided by increasing viscosity and mass density at low temperature.[4] Within a customized process mixer, ammonia's refrigerant properties could be exploited to generate these low temperatures (Note: lab observations indicate that ammonia's cooling effect upon release also mitigates spill or inhalation hazards when bound in emulsion form with a viscous oil improving pipeline safety). M3) A major advantage of ammonia oil-blending is that it greatly lowers viscosity, a 50X viscosity reduction is achieved for

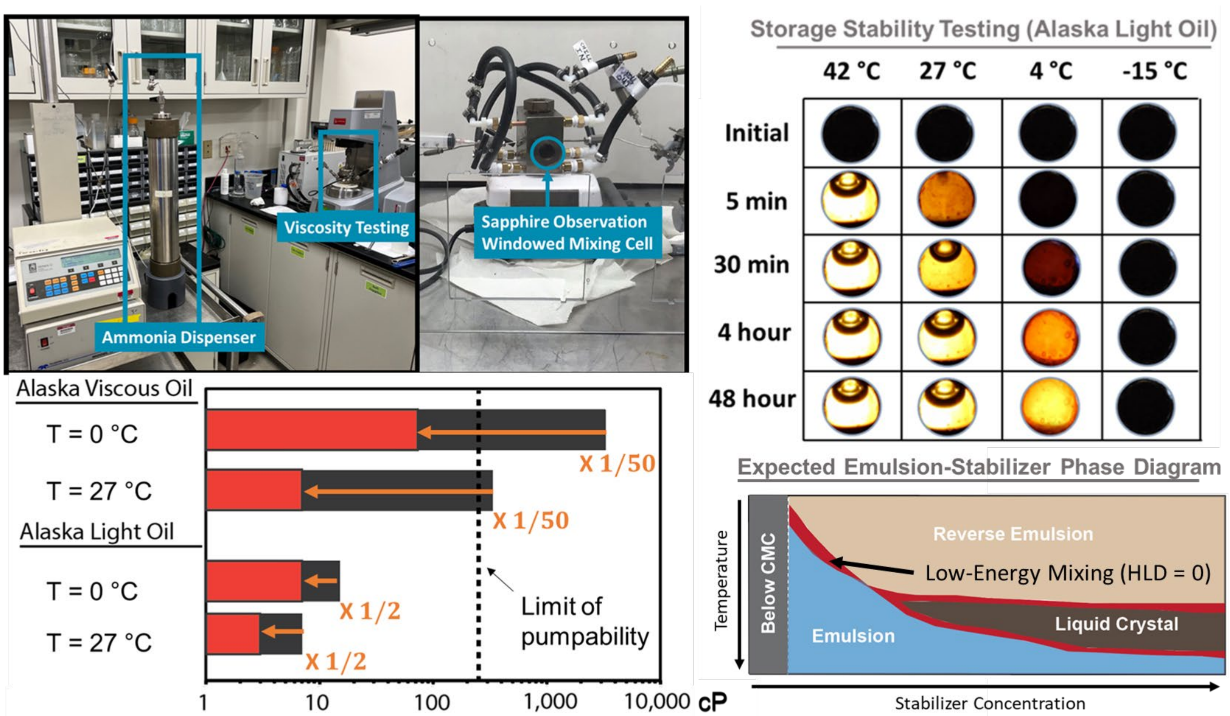


Figure 2) (*Top Left*) Experimental systems and presentation of storage stability and viscosity testing data. (*Bottom Left*) Logarithmic plot of viscosity test data shown for 60-40 oil-ammonia emulsions (5% stabilizer) prepared using either Alaska viscous oil (Schrader Bluff) or Alaska light oil (current TAPS blend) indicating 50X and 2X viscosity reduction, respectively; emulsion (orange bar) overlayed over 100% oil (gray bar). (*Top Right*) Storage stability data shown for 25-75 oil-ammonia emulsion prepared using Alaska light oil (5%Vol stabilizer) prepared under stirring at 42°C, cooled to observation temperature, and stirring ceased to estimate storage stability. (*Bottom Right*) Expected phase diagram for stabilizer used for this project with emulsion stability being promoted at lower temperatures; where HLD refers to the hydrophilic lyophilic derivation (see reference[4]).

Alaska viscous oil. This magnitude of viscosity reduction is highly enabling for applications including long-distance pipeline transport and flow through high-pressure fuel injection nozzles to improve combustion efficiency.[5] In the data presented in Fig. 2, high stabilizer concentrations were used (5%Vol), but stabilizers are costly and should be further minimized to <2%Vol. Emulsified unrefined fuels can be produced using <0.1% of total input energy, this compares to 5-10% total input energy for refined fuels delivering potential fuel cost savings. Overall, fuel emulsion product performance depends on formulation in conjunction with the ability to control mixing processes and quench to obtain a narrow droplet size distribution.

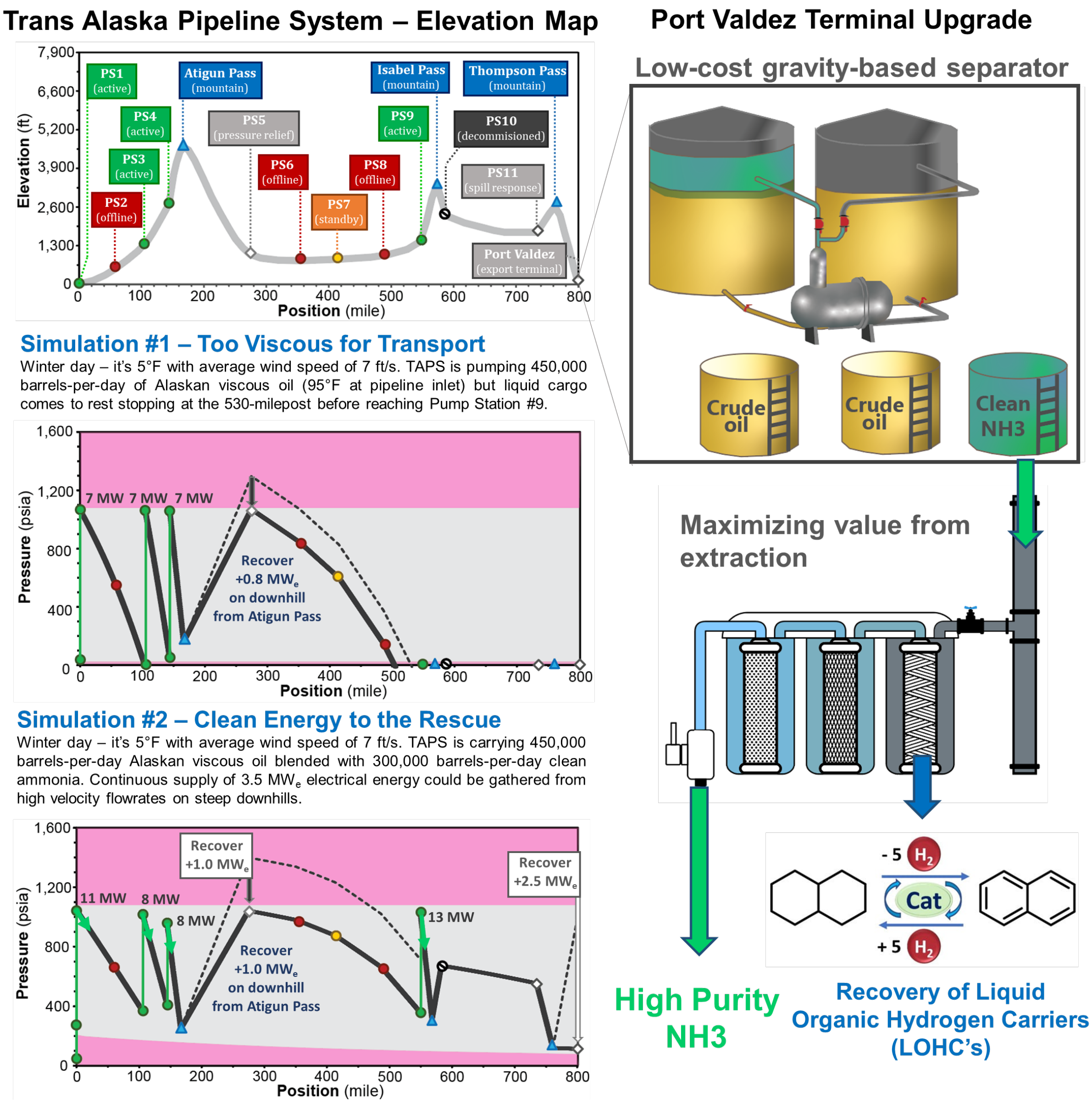


Figure 3) (Top Left) A simplified elevation vs. position map of the Trans-Alaska Pipeline System labelled with pump stations, terminals, and mountain passes. TAPS simulations were developed using the assumptions outlined in reference.[6] (Left Panel) TAPS simulations show predicted line pressure versus position. Top red region indicates TAPS' maximum allowable operating pressure, bottom red regions are when vapor formation occurs. As crude oil travels between TAPS' pump stations it loses momentum experiencing pressure drop. Comparison of the two simulations show that clean ammonia blending improves pumpability for this scenario, as well as low-flow scenarios that TAPS' experiences as productivity declines.[7] The above simulations do not account for fluid acceleration effects on mountainous downhill segments, information that Alyeska Pipeline Service Company needs for reliable operation of leak detection systems. (Top Right) A conceptual overview of a separation facility at Port Valdez to separate oil and clean ammonia is shown. Low-cost gravity-based separations are used to recover low-purity ammonia. Due to ammonia's solvent affinity for aromatic hydrocarbons (see reference[8]), an ammonia purification step could make a supply of Liquid Organic Hydrogen Carriers (LOHC's) available that may be used to inexpensively export clean hydrogen produced in coastal Alaska

The analysis in Figure 3) suggests that converting TAPS to ammonia service is technically feasible. To complete a technical feasibility study, more information is needed on the fuel emulsion technology with respect to (*i*) cavitation phenomena at pump stations, (*ii*) soft material compatibility (~80 gate check valves), (iii) a model for mountainous downhill flow supporting reliable operation of leak detection systems[9], and (iv) corrosion testing (Note: anhydrous ammonia is not considered corrosive to steel[10]). Those interested in prior TAPS recalibration proposals, see references.[11]–[13] The currently proposed ammonia blending strategy, or alternative clean energy blending methods, could be pursued by reviving a mothballed flow-loop test system located at PNNL. M4) Cost basis and lifecycle assessment in progress for "green" and "blue" pathways to be used as a marketing tool to engage Alyeska Pipeline Service Company.

What's next? We are actively looking for follow-on funding to advance the TRL of this technology in terms of emulsion stability and composition under TAPS relevant flow and P/T regimes including cost/benefit analysis. To do so, we propose to (1) perform emulsion stability studies using a laser diffraction analyzer equipped with a variable-power recirculating pump and overhead mixer to continuously circulate the emulsion system and determine oil/ammonia emulsion droplets size and size distribution; (2) use GC-MS-MS to determine oil composition in

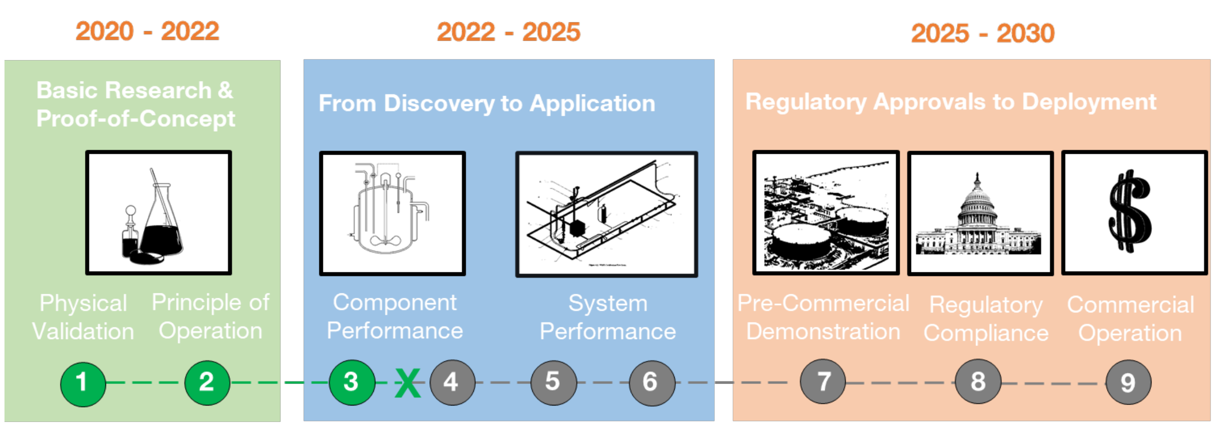


Figure 4) Current Technology Readiness Level of MightySolution^{TM} for use in pipeline transport.

the emulsion system as a function of P/T and, as needed, stabilizer concentration to estimate clean ammonia recovery costs; (3) perform a Technoeconomic Analysis with sensitivity analysis to determine materials and process cost as well as projected lifetime cost reduction when operating TAPS with MightySolution^{TM}.

Contributions Made to the Research Project. In addition to the items in this report, Mighty Pipeline graduated Alaska's Foundation I-Corps Program, Launch Alaska Tech Deployment Track, and Cascadia Clean-tech Accelerator.

What new skills and knowledge did you gain? I've learned a lot about technology commercialization and business development (*ongoing*).

Research Experience Impact on My Academic/Career Planning. Thinking about Alaska's (and Alberta's) energy transition challenges, clean hydrogen manufacturing/distribution, and founding a hard-tech start-up have become my main professional focus.

Relevance to the Mission of EERE. The overarching project goals are to improve fuel efficiency and make clean hydrogen lower cost and more accessible. The present works concerns Alaskan crude oil but informs how crude bio-oils (pyrolysis) can be likewise used. Successful commercialization of this technology can help to achieve Hydrogen Earthshot mission goals.

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