U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC), and Department of Energy Fuel Cell Technologies Office (DOE FCTO) Hydrogen Production, Distribution and Storage in Tactical Operations Workshop 2 Technical Report

Compiled by:
Scott Schramm
TARDEC Technical Advisor
10 December 2018

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Acknowledgements

The U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) acknowledges and greatly appreciates the contributions of the Department of Energy Fuel Cell Technologies Office (DOE-FCTO) in preparing for and participating during Hydrogen Production, Distribution and Storage in Tactical Operations Workshop 2 convened at TARDEC on 18 & 19 September 2018.

TARDEC also recognizes the time, effort and contributions of the technical experts who prepared/presented briefings during, participated in focused breakout sessions, and brought unparalleled experience and expertise to the Workshop. The broad-based representation from academia, industry, government agencies and military service branches educed lively discussion that produced an impressive list of Research and Development Gaps and Barriers.

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Introduction:

Following the successes of Hydrogen Workshop 1 ("H2W1" - January 2017) and displays/demonstrations (April 2017 through April 2018) of the Chevrolet Colorado ZH2 Hydrogen-fueled Army Demonstrator Fuel Cell Electric Vehicle (FCEV) it was recognized that the FCEV's hydrogen fuel requirement would require a parallel effort to identify, address and resolve technical issues associated with the generation, distribution, storage and dispensing (collectively: logistics) of hydrogen throughout all facets of military operations. H2W1 engaged military and civilian subject matter experts in a dialogue that identified options and opportunities to leverage near and far-term technologies that will enable Hydrogen to be economically, logistically and operationally viable for the U.S. Army.

Background and Objectives:

Background:

In early 2018, TARDEC and FCTO began planning of Hydrogen Workshop 2 ("H2W2"). The H2W2 Agenda (Appendix 1) was developed to intensely 'deep dive' into the logistical barriers, challenges, and opportunities presented by the use of hydrogen in Tactical Operations and general usage on military installations. The Agenda was divided into three (3) main elements:

1. Plenary Session
2. *"Near-Term Path to Transition"* Breakout Session, and
3. *"Large-Scale Hydrogen Deployments"* Breakout Session

Objectives:

The objectives of the Plenary Session were to:

- 'Level set' the participants on U.S. Army perspectives regarding: the application potential of hydrogen-fueled FCEVs, the major technical and operational gaps and barriers that must be overcome to facilitate deployment, ongoing Operational Energy Modeling & Simulation activities, and the Army's desired H2W2 outcomes.
- Provide a forum for FCTO and commercial sector stakeholders to present technical and business briefings on the current state of hydrogen generation, distribution (logistics), storage and dispensing technologies; FCEVs; and a glimpse into the near-to-long term evolution of the aforementioned.
- Appendix 2 contains Plenary Session presenters, topics and key point summaries.

The objective of the three (3), concurrent "*Near Term Path to Transition"* breakout sessions was to identify niche/early adoption applications and associated hydrogen fueling pathways; i,e., develop a basic operating scenario using the following assumptions:

- Timeframe: ~10 years from today for fielding (4 years for demonstrator)
- Development and Engineering Budget: $40M to $1B
- Application efficiency is doubled when moving to fuel cell applications
- Targeted application should consume less than 50 kg/day and support an Army echelon (real or theoretical)
- Minimize logistics burden.

While addressing the following items:

- Describe the application and refueling pathways concept.
- Outline the technologies needed, approximate maturity, and approximate cost for the system of systems
- Questions for consideration:
  - What is the ‘feedstock’ (JP-8, Water, Liquid hydrogen, etc.)? Detail.
  - Does the system reuse/recycle the water generated from the fuel cells?
  - What sort of refueling schedule does the application require and how will it be met?
  - Does the application return to a refueling point or is it refueled some other way?
  - What’s the expected system reliability?
  - Does the technology have any significant vulnerabilities?
  - What are other possible system risks?
  - What logistics support does the application require?
  - Approximately how much additional equipment does the system require?
  - Can the system be de-aggregated into reasonable-sized modules, such as ISO containers?
  - What are the primary physical transport constraints (C-17 transport, air drop, ground transport vehicle required, etc.) and how will they be resolved?

The objective of the three (3), concurrent “*Large Scale Hydrogen Deployments”* breakout sessions was to define an approach for supporting large scale adoption of hydrogen fuel cell military vehicles; i.e., develop a basic operating scenario using the following assumptions:

- Large scale adoption encompasses tactical and combat vehicles (generators to trucks to tanks) and various types of military operations
- Timeframe: 50+ years
- Development and Engineering Budget: Unconstrained
- Estimated hydrogen consumption is on the order of 10,000-50,000 kg per day
- Minimize logistics burden

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While addressing the following items:

- Describe the scale of the adoption and refueling pathways concept.
- Outline the technologies needed and technical feasibility
- Questions for consideration:
  - Are the platforms hydrogen consuming?
  - What's the fuel production strategy?
  - Is the hydrogen production centralized or distributed?
  - What is the hydrogen media (gas, liquid, liquid hydrogen carrier, solid hydrogen carrier)?
  - Is hydrogen generated in battlefield conditions or generated in a protected location?
  - Could the hydrogen be sourced from developed economies and reasonably transported into a forward location (such as how DLA sources JP-8)?
  - What hydrogen transport inefficiencies are expected (boil off, material reclamation, etc.)? Can these be mitigated (captured, recycled, etc.)?
  - What dimensional footprint is required for the system of systems, relative to fuel generation, storage and distribution?
  - Will a new material transport solution(s) need to be developed for the system (new aircraft, logistics vehicles, etc.) or are existing vehicle classes sufficient?

Scope:

- Convened on Tuesday/Wednesday 18/19 September 2018 at the Detroit Arsenal, Warren, MI in the TARDEC Design Center.
- Of the 69 Subject Matter Experts (SMEs) representing academia, industry, government agencies and military service branches/commands that registered (Appendix 3) to attend, approximately 65 participated.

Breakout Session Summaries:

- "*Near Term Path to Transition"*

  - The three (3) breakout groups agreed that light trucks, Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), and remote sensing technologies offered the highest likelihood of early adoption, but the near-term logistics burden is expected to slightly increase.
  - Candidate pathways:
    - Assembly Area on-site generation for multiple applications
    - Hydrocarbon reforming using Steam Reformation (SR) and/or Oxygen Auto-thermal Reformation (OXY-ATR)
    - Liquid / gaseous hydrogen transport
    - Metal-hydrides / Aluminum powders that promote water hydrolysis

- "*Large Scale Hydrogen Deployments*"
  - The three (3) breakout groups agreed that a broad mix of hydrogen generation and distribution technologies would be required to meet commercial or Army needs and that no one technology would emerge as "the best."
  - Two (2) of the three (3) groups reported expecting some sort of synthetic liquid fuel to still be used for aviation, and therefore would be part of military operations.
  - Technology investment recommendations focused on continuing optimization of hydrogen generation/distribution but also developing synthetic fuels for consumption or reformation from biomass or other hydrogen economy feedstocks.
  - Research & Development Gaps & Barriers:
    - Bulk distribution
    - Liquid fuel reforming
    - Modular, transportable nuclear reactor
    - Magnetocaloric liquefier
    - Fiber-reinforced pipelines
    - Modular, mobile containers
    - Modular solar/thermal-chemical water splitting
    - Direct methanol/ethanol conversion
    - Multi-fuel, adaptable tankers/barges
    - Vehicle on-board hydrogen generation (e.g. Metal-hydrides)
    - Smaller, less expensive electrolyzers
    - Generate hydrogen at point of need mixing Aluminum alloy powder with water
    - Multi-fuel reformer
    - Mature Solid-Oxide Fuel Cell (SOFC) technology to replace Proton-Exchange Membrane (PEM) FCs in specific applications
    - Modular, transportable gasifiers
    - Liquid Natural Gas (LNG) reforming
    - Efficient storage and distribution technologies that will mitigate losses
  - Candidate pathways:
    - Leverage the Automotive Industry's "push" for increasing electrification of next generation commercial and passenger vehicles
    - Investigate options and opportunities to use "Synthetic Feedstocks"

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Next Steps:

- Convene a half-to-one day "Voice of the Customer Session" workshop to directly engage military stakeholders who have responsibility for fuel logistics and infrastructure to understand and discuss hydrogen-fuel-related issues. Candidate Session locations are at CASCOM (Fort Lee) or another venue convenient for key stakeholder attendance and potential demonstrations.
- Identify specific topics for TARDEC/FCTO collaborative Research & Development to be kicked-off during Fiscal Year 2019 (FY19) and beyond.
- Initiate notional, long-range planning for Hydrogen Workshop 3 ("H2W3").
- Investigate Office of the Secretary of Defense (OSD) sponsorship for an Emerging Concept Technology Demonstration (ECTD), which could then be followed by a Joint Concept Technology Demonstration (JCTD) to further advance/accelerate the U.S. Army's development/deployment of FCEVs and related hydrogen infrastructure. An ECTD and JCTD further develops the concept and ultimately performs a COCOM-endorsed formal Military Utility Assessment.

Post Workshop MOU Signing:

On Monday 8 October 2018, National Hydrogen Day, outgoing[1] TARDEC Director Dr. Paul Rogers, and DOE-FCTO Director Dr. Sunita Satyapal; signed a Memorandum Of Understanding (MOU) "to establish a collaborative relationship … to conduct early stage research, testing, analysis, and performance assessment of fuel cell and hydrogen infrastructure-related technologies to meet Army operational energy needs and the EERE[2]-FCTO mission and its H2@Scale initiative objectives." Continuing "Initial efforts under the MOU will be … to focus upon identification and evaluation of hydrogen production, storage, transportation and dispensing in support of future military operations and nation-wide hydrogen demand scenarios."

[1] Dr. Rogers was succeeded by Mr. Jeffrey Langhout effective Monday 22 October.
[2] EERE: Energy Efficiency and Renewable Energy Office

Compiled by:

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Appendix 1

U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy	**Hydrogen Production, Distribution and Storage in Tactical Operations Workshop II** 18 & 19 September 2018	TARDEC
Detroit Arsenal – TARDEC 6501 East 11 Mile Road Warren, MI 48397-5000		
PROJECT OFFICER Mr. Kevin Centeck Supervisor, Fuel Cell Technologies Off: (586) 282 - 8537 Cell: (586) 214 - 6447	**EVENT LIAISON** Mr. Scott Schramm Technical Advisor Off: (586) 282 - 4122 Cell: (586) 306 - 4365	
Primary Meeting Location: TARDEC Bldg. 200A Design Center		
Dress Code: Business Casual		

AGENDA

Day 1: Tuesday 18 September 2018

TIME	ACTIVITY	CONTACT
0730 - 0800	Arrive Detroit Arsenal Visitors Control Center then Drive to TARDEC Bldg. 200A Reserved Parking Area	Non-Resident Invitees
0800 - 0820	TARDEC Welcome, Orientation and Introductions	Mr. Kevin Centeck
0820 - 0925	Opening Comments:	
	0820 - 0835 TARDEC	Mr. Charles Coutteau
	0835 - 0850 DOE FCTO	Mr. Ned Stetson
	0850 - 0910 Army NGCV Cross Function Teams	BG Ross Coffman
	0910 - 0925 General Motors Defense	Mr. Gary Stottler
0925 - 0945	ZH2 HFCV Tactical Performance Review	Mr. Kevin Centeck
0945 - 1010	Military Operations Hydrogen Consumption and Requirements Modeling and Simulation Results	Mr. Brian Ernst & Mr. Andrew Wiegand
1010 - 1030	Army In-Theater Operational Scenario Overviews	
	1010 - 1030 CASCOM	Mr. Charles Burden
1030 - 1045	Break and Networking Opportunity	
1045 - 1130	DOE Overviews	
	1045 - 1115 FCTO Technology Status and Targets	Mr. Pete Devlin & Dr. Ned Stetson
	1115 - 1130 Argonne National Lab Refueling Processes	Dr. Krishna Reddi

Day 1: Tuesday 18 September 2018 (Cont.)

TIME	ACTIVITY	CONTACT
1130 - 1200	Industry Overviews 1130 - 1145 Nikola Motor: H2 Path Forward 1145 – 1200 PCI: Near-Term JP8 Reforming	 Mr. Jesse Schneider Mr. Subir Roychoudhury
1200 - 1300	Non-Hosted Lunch and Networking Lunch Options Include the TARDEC Cafeteria, Special Events Food Truck and Local Off-Arsenal Restaurants	
1300 - 1400	Large Scale Hydrogen Pathways Industry Panel Session Moderated by: Air Liquide………Dr. David P. Edwards Air Products…......Mr. Brian Bonner Praxair …………....Mr. Al Burgunder	 Mr. John Christensen
1400 - 1630	**Near-Term Path to Transition Deep Dive Breakout Session** Opening Remarks Scope: Three groups independently meet on the topic. Objective: Identify niche/early adoption applications and associated hydrogen fueling pathways. Assume initially there would be low volume demand throughout the Army.	 Mr. Joseph Keusch
1630 - 1700	Breakout Session Group Work Product Out-Briefs	
1700	Adjourn	

Day 2: Wednesday 19 September 2018

TIME	ACTIVITY	CONTACT
0730 - 0800	Arrive at TARDEC Bldg. 200A Design Center	Invitees
0800 - 0815	Day 1 Out-Briefs Review and Day 2 Agenda/ Objectives	Mr. Kevin Centeck
0815 - 0830	Industry Overview NEL Hydrogen: Electrolysis	 Mr. Steve Szymanski

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Day 2 Wednesday 19 September 2018 (Cont.)

TIME	ACTIVITY	CONTACT
0830 - 1100	**Large-Scale Hydrogen Deployments Deep Dive Breakout Session** Scope: Three groups independently meet on the topic. Objective: Define the approach for supporting large scale adoption of hydrogen fuel cell military vehicles; fueled by centralized hydrogen production and liquefaction or solid hydrogen storage and subsequent distribution.	
1100 - 1145	Breakout Session Group Work Product Out-Briefs	
1145 - 1200	Senior Leader(s) Feedback, Direction and Closing Remarks	Mr. Charles Coutteau
1200 - 1215	Workshop Follow-up Summary: Key Actions, Timing And Next Meeting/Workshop Days/Dates/Venue	Mr. Kevin Centeck
1215	Adjourn	

List of Acronyms:

CASCOM	Combined Arms Support Command
DOE	Department of Energy
FCTO	Fuel Cell Technologies Office
HFCV	Hydrogen Fuel Cell Vehicle
JP8	Jet Propellant 8 (Army's primary liquid fuel)
NGCV	Next Generation Combat Vehicle
TARDEC	Tank Automotive Research, Development and Engineering Center

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Appendix 2

Plenary Session Briefings Key Points:

BG Ross Coffman - Next Generation Combat Vehicle Cross Function Team

The keynote was presented by Brigadier General Ross Coffman, U.S. Army, Director; Next Generation Combat Vehicle Cross Functional Team. He discussed the imperative of having technological superiority over adversaries many of which have numerical advantages. BG Coffman is looking forward to seeing the results of the workshop and the determination whether fuel cell tactical vehicles will provide a true 'silent watch' capability without overburdening the logistics system.

Mr. Charles Coutteau – TARDEC

- Electrification enables a multi-domain operational capability
  - Extreme agility
  - Enhanced Situational Awareness
  - Hemispheric Lethality and Protection
  - Reduced Footprint
  - High Dash Speed and ability to negotiate obstacles
- Where are we today?
  - First Prototype Commercial Fuel Cell Tactical Vehicle
  - First Prototype JP-8 Reformer
  - First Prototype Tactical Hydrogen Operational Refueler
- Where do we want to go near term?
  - 2^{nd} Prototype Tactical Hydrogen Operational Refueler
  - Hydrogen Transportation and Distribution Trailer
  - Robust Military Relevant Tactical Fuel Cell Vehicle
- Where do we want to go far term?
  - Hydrogen Logistics
- Develop path forward to move large quantities of hydrogen
- Research, develop and test hydrogen generation technologies
  - Future Vehicle Direction - Develop hydrogen fuel cell based combat vehicle
- Combine commercial fuel cell stacks into larger power system
- Build cooling system to address increased cooling requirement
- Integrate hydrogen storage to meet range requirements
- Outcomes of this workshop
  - Address how the DoD can store distribute and dispense hydrogen in support of global expeditionary operations
  - Provide input for a hydrogen infrastructure technology roadmap

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Dr. Ned Stetson – DOE Fuel Cell Technology Office (FCTO)

- Hydrogen and Fuel Cell Progress
  - The cars are here. Fuel Cell Electric Vehicles (FCEVs are being leased/sold in CA by Toyota, Honda, and Hyundai
  - FCEVs getting ~60mpg (equivalent) and up to 360mi range
  - 35 retail H2 stations in CA. 12 coming to the northeast U.S.
  - 650 MW of Fuel Cell power shipped in 2017, up from 500 MW in 2016. $2B in fuel cell revenue in 2017
- DOE FCTO Program Focus and Research Targets
  - Primary focus: Applied research, development and innovation in hydrogen and fuel cell technologies. Mostly early stage R&D
  - Subprograms: Fuel Cells, Hydrogen Fuel, Infrastructure R&D
- Hydrogen Fuel Cell Current and Projected Costs
  - Production, Delivery and Dispensing: $13-16/gge to $5-10/gge
  - 700 bar onboard storage: $24/kW to $15-17/kW
- H2@Scale Vision: Enable affordable, reliable, clean and secure energy across multiple sectors
  - Nearly 30 million metric tons of potential hydrogen demand in the U.S.
  - Most regions in U.S. have sufficient hydrogen resources
- DOE Early Stage Research on Fuel Cells:
  - Low - PGM and PGM-free catalysts
  - Durability and performance of membranes, bipolar plates, electrodes, etc.
  - Platinum loading improvement
- DOE Early Stage Research on Hydrogen Delivery:
  - Gaseous & liquid delivery, compressors, storage, dispensers, materials compatibility, liquefaction, pipeline & joining materials
- DOE Early Stage Research on Hydrogen Storage:
  - Low cost carbon fiber precursors for high pressure H2 storage
  - Advanced hydrogen storage with higher energy densities and favorable thermodynamics
  - Hydrogen carriers and bulk storage to enable H2@Scale
- Other DoD applications: Army man-wearable power, UAVs, UUVs

Mr. Garry Stottler – General Motors Defense

- Key conversion factors:
  - 1.08 gal JP8 + 1.48 gal H20 = 1 kg of H2
  - 1kg H2 + O2 from Air = 2.4 gal H2O (2/3 liquid + 1/3 vapor)
- GM & Honda Joint Manufacturing Venture
  - 50:50 Manufacturing Joint Venture announced January 2017
  - Manufacturing Location: Brownstown Township, MI
  - $85 Million initial investment, creating new jobs in MI
  - Fuel cell production around 2020 Gen 2 Fuel Cell System
  - Extensive automation: product based on shared R&D program
  - Technology becoming affordable for automotive applications

- Unique benefits of military FCEV applications
  - Drive cycle/duty cycle positioning advantageous to FCEVs
  - Clean, cool, quiet = improved stealth capability
  - Efficient power production for advanced systems
  - Potential for tailored hydrogen supply infrastructure
  - Fuel Cell water recovery = reduced logistics;
    - The water ends up where the vehicles are
    - Meet front line needs or make more hydrogen
  - Increased efficiency = reduced logistics
- GM Defense: Leveraging strengths from hydrogen fuel cells:
  - Power to spare
  - Adaptability
  - Range
  - Export Power (80kW)
  - 5 minute fast refueling
  - Minimized Detection
  - Fast refueling
  - Water Recovery system
  - Electric Drive
  - Reduced noise and thermal signature

Kevin Centeck, TARDEC - ZH2 HFCV Tactical Performance Review

- Purpose: Present the reasons why the military is pursuing hydrogen fuel cell vehicles, what was learned over the ZH2 evaluation period, and results of some safety testing
- Discussion of the TARDEC Public-Private-Partnership with General Motors and how it is benefitting both organizations
- Layout of the ZH2 program from concept to vehicle delivery
  - Discussed the requirements transfer to a commercial based fuel cell vehicle
  - Discussed the rapid prototyping capability of a non-traditional contractor
- Dual path development of the logistical support equipment that would enable a fuel cell vehicle demonstration
  - JP-8 reformer unit built by Battelle to convert JP-8 fuel into clean hydrogen for vehicle use
  - 20 foot ISO container for hydrogen storage and dispensing to the vehicle; Tactical Hydrogen Operational Refueler (THOR)
- Plan of demonstrations and evaluations over the 12 month TARDEC evaluation period with the ZH2; including locations, conceptual operational plan, and timing
- Review of the biggest takeaways from the soldiers during the evaluations
  - Silent Mobility
  - Silent power available for export
- Review of the acoustic and thermal signature testing performed under the ZH2 effort
- Discussion of the benefits and flexibility of the varying hydrogen generation technologies that can be leverage besides just JP-8 reforming.

- Presentation of the ballistic testing performed on the hydrogen tanks used in the ZH2 and some other tanks made available.
  - 7.62 ballistic test data
  - RPG test data
- Discussion about fuel cell power system flexibility through combining multiple systems into a cohesive larger power system
- Discussion of the TARDEC Fuel Cell Technologies team path forward in powering a combat platform with hydrogen and fuel cell power.

Messrs. Brian Ernst and Andrew Wiegand (TARDEC) - Military Operations Hydrogen Consumption and Requirements Modeling and Simulation Results

- Purpose: Develop a concept of operations for hydrogen generation, storage, and distribution in Army relevant operations.
- Focus: How would we implement fuel cell technologies on the battlefield?
  - Decision: focus on motorized Infantry Brigade Combat Team (IBCT)
  - IBCT currently has minimal vehicles. Motorized IBCT gives everyone a seat
- Estimating hydrogen consumption
  - Fuel Cells can reduce the energy consumed on the battlefield
  - Most impact: Full adoption w/ high storage density (solid H2)
    - However, solid H2 is low-TRL technology
  - GMV and generators have minimal energy impact in combat
  - JP-8 Reformation increases energy consumption
- Summary and conclusions
  - Hydrogen generation, storage, and distribution is complicated with no “best” solution.
  - Tactical advantages and energy reduction must be balanced with logistics needs
  - JP-8 reformation is best suited to niche applications to minimize logistics burden
  - Long term, high density hydrogen storage is crucial
  - Current technology forces us to light vehicles at low quantities.
  - Future technology enables feasible adoption at a brigade level

Mr. Charles Burden, CASCOM – Army In-Theater Operational Scenarios

- Service/Agency Responsibilities:
  - The Army provides overland distribution of bulk petroleum support, including inland waterways for all DOD components
  - The Navy provides seaward and over-the-shore bulk petroleum products to the high-water mark for sea -based and land-based forces of all DOD components. The USN maintains the capability to provide bulk petroleum support to naval forces afloat and ashore (to include US Coast Guard forces assigned to DOD).
  - The Marine Corps maintains a capability to provide bulk petroleum support to its units.
  - DLA Energy manages the bulk petroleum supply chain from source of supply to the point of customer acceptance

  - Each DOD Joint Petroleum Office has the primary responsibility of synchronizing the fuel requirements throughout the joint force.
  - The Air Force maintains the capability to provide tactical support to USAF units at improved and austere locations. It also provides distribution of bulk petroleum products by air where immediate support is needed at remote locations.
- How The Army Receives, Stores and Distributes Petroleum
  - Inland Petroleum Distribution System (IPDS) Pipeline
    - 3-5 miles pipeline laid per day; 1.1M gal/24 hrs throughput
  - Early Entry Fluid Distribution System
    - 2 km fluid transfer hose and communication cables
  - Tactical Petroleum Terminal (TPT)
    - Army's primary capability for large bulk storage at Strategic and Operational levels
    - Comprised of three 1.26M gallon fuel units (3.78M total capacity)
    - Operated by the Petroleum Pipeline and Terminal Operating Company.
    - Is the fuel source for line haul truck companies
    - Within a pipeline trace TPTs form the base, head and (if needed) intermediate terminals.
  - Fuel System Supply Point (FSSP)
    - Army's primary capability for large bulk storage at Operational and Tactical levels
  - Assault Hoseline System (AHS)
    - Flexible hoseline system for transporting fuel between bulk storage locations a relatively short distance
  - Line Haul and Tactical Haul (M1062, 7500 gal; M967, 5000 gal)
    - Semitrailers are the primary means of moving petroleum long distances from strategic level to the maneuver elements.
    - M1062 is the largest semitrailer and line hauls from strategic/operational as far forward as the tactical area
    - M967 line hauls similar to M1062 but increased mobility allows travel on unimproved and off road as far forward as maneuver elements
  - Retail Refueling Systems (Tank & Pump Unit, Heavy Mobility Tactical (HEMTT) Tanker, Tank Rack Module, M969 semitrailers)
    - Tank & Pump Units provide internal retail capability primarily to Headquarters, Truck Companies, Military Police and Chemical (also using with water for decontamination)
    - HEMTT Tankers and Tank Racks are the primary systems for refueling consuming platforms within brigade combat teams and support brigades
    - M969 retail semitrailers provide area support to echelon above brigade units, aviation brigade retail, and bulk backup retail support to brigade combat teams

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Mr. Pete Devlin, DOE FCTO - FCTO Technology Status and Targets

- Emerging Applications
  - Fuel Cell Parcel Delivery Trucks: in delivery service
  - Fuel Cell Buses: carried 19M passengers
  - Heavy Duty Fuel Cell Truck: being demonstrated
  - Tactical Fuel Cell Truck: GM ZH2 tested out favorably
  - Fuel Cell Stationary/Primary power: World Trade Center
  - Fuel Cell Backup Power: survived multiple hurricanes
- Interagency Coordination and Collaborations
  - Fuel Cell Forklift success story: agency-sponsored demonstrations led to over 20,000 now being deployed
  - Possible DoD areas of collaboration include:
    - Soldier (wearable)power
    - Portable power (gensets)
    - UAVs and UUVs
    - Medium and heavy duty trucks
    - Marine power
    - Stationary power
  - H2 Generation and Infrastructure in Remote Areas
    - Two day TARDEC-FCTO workshop with 40 participants held in January 2017
    - Investigated near and long-term technical approaches for hydrogen generation via Electrolysis or Reformation
  - Outcome: Identified critical needs for tactical hydrogen infrastructure in remote areas
  - Workshop followed by an evaluation of ZH2 Advantages:
    - On-board water production
    - Exportable electric power
    - Near silent operation
    - Extreme off-road capability
- Fuel Cell and Infrastructure Priorities:
  - Hydrogen Delivery R&D
    - Use of modern, high-strength steels in hydrogen pipelines
    - Novel concepts for compression (electrochemical, metal hydride)
    - Innovative integrations of hydrogen station compression and storage
    - Non-mechanical approaches to liquefaction
    - Thermodynamic analysis of liquid hydrogen transfers and boil-off mitigation strategies.
    - Wire-wrapped pressure vessels for low-cost storage
    - Novel hoses for reliable, low-cost dispensing
  - Other R&D
    - Integrated control & dispatch of renewable hydrogen
    - Class 8 Long Haul Fuel Cell Truck Targets
    - Autonomous Hydrogen Fueling Station

Dr. Krishna Reddi, DOE ANL - Argonne National Lab Refueling Processes

- Hydrogen Refueling Modeling and Analysis
  - User-Defined Model Inputs: Market, Technical and Economic
  - Technical: Mode of hydrogen delivery (e.g., gaseous, liquid); fill amount; fueling speed, hourly fueling demand
  - Compressor is the most costly refueling component but is oversized and underutilized
- Pressure Consolidation Analysis: Pressure consolidation exploits the relationship between suction pressure and compressor throughput. Proof of concept testing conducted at NREL.
  - Pressure consolidation benefits appear to include:
    - Higher compressor throughput during peak demand
    - Consistent high SOC fills with sequential back-to-back fills
    - Reduced compressor size (compared to w/o consolidation) for a given daily demand, or increased compressor throughput (2X:3X) to accommodate growing refueling demand
      - 25-30% reduction of refueling equipment cost
      - of interest to diaphragm compressors due to limited volume displacement
    - Improved tube-trailer (or supply storage) utilization
      - Reduced cost of delivered hydrogen
      - Improved logistics (less frequent deliveries)
    - Improved compressor reliability
      - Less frequent starts and stops

Mr. Jesse Schneider, Nikola Motor - Nikola Motor: H2 Path Forward

- Fuel Cell Semi-truck: 800 on order, 8000 planned. 240kW fuel cell.
- Hydrogen Infrastructure:
  - Initial stations in 2019-2020. 30 H2 stations by 2023
  - 400+ stations planned by 2028
  - Public access
  - On site hydrogen creation via alkaline electrolysis
- Station Highlights:
  - 700 MPa fast fueling (10 minutes)
  - Capable of dispensing 80 kg of H2 in ten minutes
- Opportunities for DOD collaborations:
  - Utility Vehicle development
  - Shared hydrogen infrastructure

Mr. Subir Roychoudhury, PCI - Near-Term JP8 Reforming

- Current pathways to produce power from PEM FC are energy intensive and require several processing steps •
- Future opportunities such as using SOFC systems offer less complicated processing and are less energy intensive

- H2 Generation Pathways for Battlefield Power
  - Water electrolysis (PEM)
    - H2 Generation via PEM water electrolysis requires up to 1.5x the amount of electrical energy required for SOEC water electrolysis
  - Steam Reform Desulfurized JP8
    - 80% H2 Separation Efficiency with no change over 250 hrs
  - Oxy – Auto Thermal Reforming (ATR) of JP8
    - Turnkey Syngas Generation Skids and High Pressure Reactor ~14 kg H2/day
    - Operated over 5,000 combined run time; Produced >60,000 Nm3 of syngas
  - JP-8 Reformer Integrated with Solid Oxide Fuel Cell
    - No separation purification required
- Longer Term Option: JP-8 onboard Oxy-ATR H2 generation and desulfurization

Mr. Steve Szymanski, NEL Hydrogen – Electrolysis Pathways

- Supply Agreement for Nikola Station Network
  - AZ & CA for Demonstration + 448 Station Network, USA
- NEL is working on a GIGA factory concept for renewable hydrogen production achieving fossil parity
  - 8 stack cluster (~20 MW) provides the basis for grid scale plants
  - Target is to reach <$500/kW and manufacturing scale
- Heavy Duty Vehicles and buses will help provide scale to hydrogen
  - High pressure trailers can achieve low distribution costs
    - Multiple companies are progressing with 50-70MPa trailers
    - Using type 3 or 4 vessels to reduce weight and increase payload
    - Target capacities ranges from 300-1,500 kg per trailer
    - Designed with several banks for optimal product transfer
    - Up to 40 foot sized trailers used for dump-off or parking
    - 20 foot sized bulks used for swapping at site
    - Efforts based on experience from CNG distribution
  - High pressure trailers will greatly reduce distribution costs
    - Will get close to the distribution cost levels of liquid
    - Sufficiently low to enable trucking from renewable production sites
- Supply agreement with Shell for stations in CA
  - Example of a delivered hydrogen installation model
- Hydrogen Brentwood NPS Demonstration Station, Washington DC
- Hydrogen Energy Storage for Microgrid Project, Appleton, WI
- Power to Gas Demonstration Project, University of California Irvine, Sponsor: SoCal Gas

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Large Scale Hydrogen Pathways Industry Panel Session

- **Dr. David Edwards – Air Liquide**
- **Mr. Brian Bonner - Air Products and Chemicals**
- **Mr. Eric Dirschka - NASA Kennedy Space Center**
- **Dr. Dan Flowers - Lawrence Livermore National Lab**

The speakers discussed their perspective on producing, distributing, and storing hydrogen. Dr. Edwards and Mr. Bonner spoke from an existing industry perspective. Eric Dirschka is involved in the procurement of hydrogen for NASA and presented a customer perspective. Dr. Flowers discussed cryo-compressed hydrogen, an emerging capability being pioneered at LLNL. While not yet at scale, this technology is one that could transport even more hydrogen. The audience questions were wide-ranging, and significant information was exchanged. Even so, the panel session was inconclusive.

Industrial gas suppliers are still defining a long-term plan for large scale adoption of hydrogen and highlighted concern that the scale needed for high commercial market penetration of fuel cells is beyond current industrial technology capabilities. The NASA and Lawrence Livermore National Laboratory participants emphasized that while they agree with the assessment, the technology seems feasible.

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Appendix 3

Hydrogen Workshop 2 Registrants

Last Name	First Name	Title	Affiliation
Ahluwalia	Rajesh		DOE ANL
Anderson	Mike	Dr.	U.S. Army TARDEC
Blum	John J.		Triton Systems
Bonner	Brian		Air Products
Bowen	Brandon J.		U.S. Air Force
Bucci	Michael		Plug Power
Burden	Charles (Chuck)		U.S. Army CASCOM
Burgunder	Al		Praxair
Centeck	Kevin		U.S. Army TARDEC
Chrisitan	Andrew		Nikola Motor Company
Christensen	John		DOE FCTO/NREL
Chu	Deryn	Dr.	U.S. Army ARL
Colquitt	Chris		General Motors Corp.
Combs	Patrick		U.S. Army TARDEC
Devlin	Peter		DOE FCTO
Dirschka	George E. (Eric)		NASA - KSC
Drotleff	Kari		U.S. Army TARDEC
Dusenbury	James	Dr.	U.S. Army TARDEC
Dwornick	Bridget		U.S. Army TARDEC
Edwards	David P.	Dr.	Air Liquide
Elhonsi	Maroune		GDLS
Ernst	Brian		U.S. Army TARDEC
Fassino	John		OSD Operational Energy
Flowers	Dan		DOE LLNL
Fox	Mark		U.S. Army TARDEC
Fuchs	Alice M.		Mass Transportation Authority
Giri	Anit		U.S. Army ARL
Ignash	Mark E.		MEDC
Jakubowski	Vince		PM Force Projection
Jakupca	Ian		NASA - Glenn
Keegan	Sarah		General Motors Corporation
Kelly	James (Jim)		U.S. Army CASCOM
Keusch	Joseph (Joe)		U.S. Army PEO CS&CSS
King	Adam		General Motors Corporation
Kler	Timothy		U.S. Army PEO CS&CSS
Koonce	Michael		Luxfer – GTM Technologies
Layne	Thomas R.		U.S. Air Force AFRL/RX
Leffler	Matthew C.		DOE LLNL
Mann	Margarita		General Motors Corporation
Matteson	Ian		UUV Test Vehicles Branch

Last Name	First Name	Title	Affiliation
McNenly	Matthew		DOE LLNL
McWorter	Scott		DOE SRNL
Mercurio	Joe		General Motors Corporation
Mishler	Jeff		Ardica
Odom	Sarah J.		Electricore, Inc.
Ortmann	Walt		Ford Motor Company
Osserman	Stanley J.		HCATT
Peters	Michael		DOE NREL
Reddi	Krishna	Dr.	DOE ANL
Roychoudhury	Subir		PCI
Saber	James (Jim)		NextEnergy
Schneider	Jesse		Nikola Motor Company
Schramm	Scott		U.S. Army TARDEC
Scruggs	Andrew	MAJ	U.S. Army TARDEC
Shipp	Charles W.		U.S. Army Petroleum Center
Simelaro	Robert (Bob)		U.S. Army TRADOC/ARCIC
Sokolsky	Steven		CALSTART
Spitzer	Kevin		U.S. Air Force AFRL
Sprik	Sam		DOE NREL
Stetson	Ned	Dr.	DOE FCTO
Stottler	Gary		General Motors Corporation
Szczesny	Eric		U.S. Army TARDEC
Szymanski	Steve		nel Hydrogen
Tamburello	David A.		DOE SRNL
Taylor	Robert	LTC	U.S. Marine Corps
Waters	Ryan C.	LTC	U.S. Army NGCV-FCT
Woodard	Alan		U.S. Army CASCOM

List of Acronyms:

AFRL: Air Force Research Laboratory
ANL: Argonne National Laboratory
ARCIC: Army Capabilities Integration Center
ARL: Army Research Laboratory
CASCOM: Combined Arms Support Command
CS&CSS: Combat Support & Combat Service Support
DOE: Department of Energy
FCT: Futures Command
FCTO: Fuel Cell Technologies Office
GDLS: General Dynamics Land Systems
HCATT: Hawai'i Center for Advanced Transportation Technologies
KSC: Kennedy Space Center
LLNL: Lawrence Livermore National Laboratory
LTC: Lieutenant Colonel
MAJ: Major
MEDC: Michigan Economic Development Corporation
NASA: National Aeronautics & Space Administration
NGCV: Next Generation Combat Vehicle
NREL: National Renewable Energy Laboratory
OSD: Office of the Secretary of Defense
PEO: Program Executive Office
PM: Program Manager
SRNL: Savannah River National Laboratory
TARDEC: Tank Automotive Research, Development & Engineering Center
TRADOC: Training & Doctrine Command
UUV: Unmanned Underwater Vehicle