IV.E.5 Early Market TRL/MRL Analysis

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Fiscal Year (FY) 2012 Objectives

- Determine methodology for Technology Readiness Level/Manufacturing Readiness Level (TRL/MRL) analysis of technology and manufacturing readiness of early market motive and non-motive hydrogen storage technologies.
- Prepare and send out questionnaire to developers and manufacturers of hydrogen storage technologies for self-assessment to assign TRL/MRL.
- Analyze TRL and MRL of early market hydrogen storage technologies.
- Deliver a TRL/MRL analysis to reveal state of the art of technology and manufacturing readiness and to identify research and development (R&D) gaps.

Technical Barriers[1]

This project aids the DOE in understanding the technology readiness levels and manufacturing needs for hydrogen storage technology for use in fuel cell motive and non-motive early market applications. The findings will be used to identify technology gaps in the following:

- System Weight and Volume
- System Cost
- Durability/Operability
- Charging/Discharging Rates
- Materials of Construction
- Manufacturing

[1] The technical barriers listed in the DOE Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan pertain to light-duty vehicles and are not applicable to this project.

Technical Targets

To assess technology and manufacturing readiness of early market hydrogen storage technologies, PNNL requested developers and manufacturers to assign TRL and MRL to their technologies based on a self-assessment. The TRL/MRL levels are related to above technical barriers, although they are not quantifiably addressed in this report.

FY 2012 Accomplishments

- Developed a TRL/MRL questionnaire and sent out to technology developers and manufacturers to perform a self-assessment to learn technology readiness for manufacturing.
- Analyzed questionnaire results with assigned TRL/MRL to each hydrogen storage technology based on material and application to identify state of the art.
- Performed a TRL/MRL analysis to reveal technology and manufacturing readiness levels and identify gaps to provide programmatic recommendations to DOE.

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Introduction

Fuel cells (FCs) are considered a key future energy efficient power generation technology. The DOE's Fuel Cell Technologies Program (FCTP) is focused on key challenges concerning fuel cells and hydrogen technologies including hydrogen production, delivery, distribution and storage. Recently, the FCTP has broadened its focus from light-duty vehicle application to include near-term market applications, and hydrogen storage is necessary for these fuel cell applications [1,2]. The focus of this report is hydrogen storage for near-term commercial fuel cell applications. The report documents the methodology and results of an effort to identify hydrogen storage technologies' technical and manufacturing readiness for early market motive and non-motive applications and to provide a path forward toward commercialization. Motive applications include materials handling equipment (MHE) and ground support equipment, such as forklifts, tow tractors, and specialty vehicles such as golf carts, lawn mowers and wheel chairs. Non-motive applications are portable, stationary or auxiliary power units and include portable laptops, backup power, remote sensor power, and auxiliary power for recreational vehicles, hotels, hospitals, etc.

The Technology Readiness Assessment (TRA) is based on a combination of TRL and MRL designations that enable evaluation of hydrogen storage technologies in varying levels of development [3,4]. This approach provides a logical methodology and roadmap to enable the identification of hydrogen storage technologies, their advantages/disadvantages, gaps and R&D needs on an unbiased and transparent scale that is easily communicated to interagency partners.

Approach

To assess the state of the art of hydrogen storage technologies for motive and non-motive early market applications, PNNL performed a Technology Readiness Assessment (TRA) to learn market and technology readiness and to provide a path forward to bring the hydrogen technologies to maturity. The technology development model is illustrated in Figure 1.

PNNL prepared a questionnaire to assign TRL and MRL for each hydrogen storage technology. The definitions of TRL/MRL are provided in Table 1. The manufacturing status is established from eight risk elements: technical maturity, design, materials, cost & funding, process capability, personnel, facilities and manufacturing planning. The questionnaire was sent to hydrogen storage technology developers and manufacturers who were asked to perform a self-assessment. We included both domestic and international organizations including U.S. national laboratories, U.S. companies, European companies and Japanese companies. PNNL collected the data and performed an analysis to deduce the level of maturity and to provide program recommendations. The TRA report documents the process used to conduct the TRA, reports the TRL and MRL for each assessed technology and provides recommendations based on the findings.

Results

For the TRL/MRL analysis, we targeted technology developers and manufacturers, both U.S. and foreign, with an advanced hydrogen storage material in a subsystem or system. Out of 32 requests for self-assessments, 25 invitees participated. The requests for participation were sent out by email during summer/fall 2011 and the TRA-analysis was performed in winter/spring 2011-2012. Following is a summary of key results of PNNL's TRA-analysis of each hydrogen storage technology and intended application.

Metal Hydrides TRL/MRL Analysis

Metal hydrides' technical maturity, based on 12 replies, is between TRL 3 and 9, indicating that there are metal

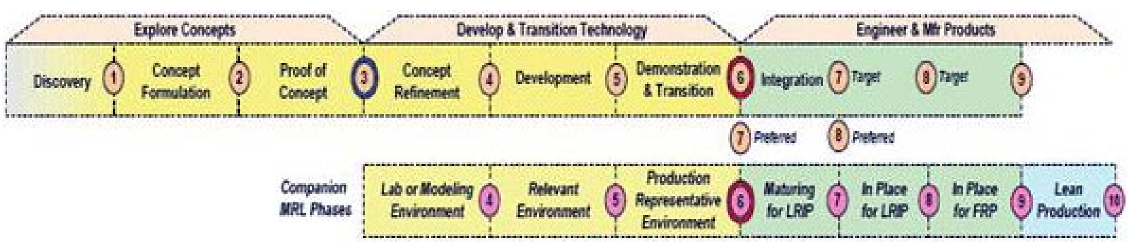

FIGURE 1. Technology Development Model

TABLE 1. Definitions of Technology and Manufacturing Readiness Levels (TRL and MRL)

Levels	TRL	MRL
1	Basic principles observed and reported	
2	Technology concept and/or application formulated	
3	Analytical and experimental critical function and/or characteristic proof of concept	
4	Component and/or breadboard system validation in laboratory environment	Capability to produce the technology in a laboratory environment
5	Component and/or brassboard system validation in relevant environment	Capability to produce prototype components in a production-relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment	Capability to produce systems or subsystems in a production-relevant environment
7	System prototype demonstration in an operational environment	Capability to produce systems, subsystems or components in a production-representative environment
8	Actual system completed and qualified through test and demonstration	Pilot Line Capability demonstrated; ready for Low Rate Initial Production
9	Actual system operated over the full range of expected mission (operating) conditions	Low Rate Initial Production demonstrated; capability in place to begin Full Rate Production
10		Full Rate Production demonstrated and lean production practices in place

hydride materials with advanced maturity and that are ready for commercialization with great potential for early market applications. The manufacturing readiness is between MRLs 3 and 10, signifying that the metal hydride technologies' manufacturing process has been developed for certain applications and that low rate initial production (LRIP) and even full rate production (FRP) are in progress.

The participants provided the following intended applications and TRL/MRL for metal hydrides:

- material handling equipment with TRL 7-9 and MRL 4-7
- portable applications with TRL 9 and MRL 10
- stationary storage with TRL 4-9 and MRL 4-9
- storage for both high-pressure and low-pressure needs with TRL 5-9 and MRL 5-8
- auxiliary power units with TRL 4 and MRL 4
- mobile/vehicular applications with TRL 4-6 and MRL 4-7

Chemical Hydrogen Storage Materials TRL/MRL Analysis

The chemical hydrogen storage materials' technical maturity, based on three replies, is between TRL 3 and 5 for three different materials, i.e. magnesium hydride slurry, ammonia borane and sodium borohydride. Prototypes have been demonstrated for single-use/disposable hydrogen storage for portable and emergency power applications. In addition, one of the technologies has been integrated in breadboard evaluation. The manufacturing readiness is low at MRL 2, indicating that the manufacturing concept has been defined but not developed. Before reaching LRIP, integrated systems need to be demonstrated to transition the technologies.

Sorbents TRL/MRL Analysis

We could identify one sorbent technology developer with an advanced sorbent material, AX-21/Maxsorb, in large-scale quantities; the application is for cryosorption and intended for storage and transportation. The technical maturity was indicated as TRL 6, which indicates that a prototype has been demonstrated in a relevant environment, but a fully integrated system has not been built. The manufacturing readiness is low at MRL 2, indicating that a manufacturing concept has been defined but not developed.

Hydrogen Storage Cylinder TRL/MRL Analysis

Based on nine replies from tank developers and manufacturers, the TRL for hydrogen storage cylinders is 4-9. Pressure vessels for gaseous and cryo-compressed hydrogen storage are an advanced technology, which is not surprising since there are already commercially available products using hydrogen storage cylinders with fuel cells, such as MHEs, including forklift fleets. The pressure vessel technology is suitable for early market applications, especially motive applications.

The participants provided the following intended applications and TRL/MRL for hydrogen storage cylinders:

- Type 1 cylinder for hydrogen powered industrial trucks with TRL 9 and MRL 7
- Type 3 cylinder for gaseous hydrogen storage with TRL 8-9 and MRL 5-8
- Type 4 cylinder for gaseous hydrogen storage with TRL 4-5 and MRL 4-6
- Cryogenic pressure vessel for vehicles with TRL 5-6 and MRL 4-6

Conclusions and Future Directions

PNNL performed a technology and manufacturing readiness assessment based on existing DOE TRA and MRA procedures adapted for hydrogen storage technologies to learn the current readiness for early market applications. The manufacturing status could be established from eight risk elements: technical maturity, design, materials, cost & funding, process capability, personnel, facilities and manufacturing planning.

PNNL assisted in identifying candidates for the self-assessments, providing a questionnaire to company points of contact, and collected the data. The replies were validated to ensure consistency and the data was analyzed to establish the status of hydrogen storage technologies based on given TRL/MRL. The replies were anonymous and the assigned TRL/MRL is not tied to any company name.

Key Conclusions

The following key conclusions on hydrogen storage technology maturity could be made based on the TRL/MRL analysis:

- The highest TRLs for existing technologies are for metal hydrides with TRL 7–9 and gaseous storage with TRL 8–9; these are most promising for early markets.
- For metal hydrides, the highest risk elements for manufacturing readiness were identified as process capability, facilities and manufacturing planning.
- Integration of metal hydrides in motive applications is underway, specifically MHE applications, i.e. forklifts, in several global demonstration and deployment projects.
- Materials development programs are needed to replace the expensive rare-earth metal hydrides typically used in MHE applications with low-cost, abundant metals.
- Hydrogen storage cylinders (Types 1 and 3) have been demonstrated in relevant environments for compressed gas storage and LRIP is in progress, ready for FRP if

demand increases. Funded efforts to decrease cost are already in progress.

- Cryo-compressed hydrogen storage has TRL 5–6 with systems validated in relevant environments and one integrated prototype demonstrated onboard a vehicle. MRL 4–5 was given, indicating a low level of readiness for LRIP.
- Metal hydrides for stationary storage of auxiliary power units could also have an impact on early markets, but systems integration efforts would be necessary as a first stage.
- Chemical hydrogen storage canisters/cartridges are to a limited extent commercially available for non-motive applications, especially portable power, but market demand is low and technology transition programs are recommended.
- Chemical hydrogen storage materials are still in need of technology development and appear to be more suitable for mid-term or long-term markets with a few exceptions.
- Sorbent materials have not advanced beyond TRL 2, except for one material which has TRL 5, but is not yet ready for transition to LRIP. An integrated system needs to be demonstrated to proceed toward LRIP, and sorbents appear to be more suitable for mid-term to long-term markets.

Recommendations and Future Directions

Based on the TRA analysis with assignments of TRL and MRL of hydrogen storage technologies based on metal hydrides, chemical hydrogen storage materials, sorbent materials and pressure cylinders, and also specific applications, the following programmatic recommendations are made.

- Metal hydrides are identified to have the greatest impact on the early markets for MHE and ground support equipment, such as forklifts and trucks, provided that funds are provided for systems integration, demonstration and deployment in relevant environments and this is a recommended area for DOE support.
- To reach early commercialization of advanced metal hydride-based technologies, focus needs to be on process capability, facilities and manufacturing planning to reach LRIP and market and technology transformation programs are recommended.
- Chemical hydrogen storage materials are identified to have greatest impact on the early market for portable power and consumer electronics if using one-use cartridges for disposal or recycling. Only a few products are commercially available, main reason due to low consumer demand. It is recommended that DOE supports technology transition projects to advance the technology and lower cost. An infrastructure project to implement solutions for recycle systems would bring cost down and provide the user with a familiar system similar to that for batteries.
- Many chemical hydrogen storage materials and complex metal hydrides show promise for commercialization, but may realistically be for mid-term to long-term markets since materials development is still in progress and is therefore not recommended for early market demonstrations, rather materials and technology development programs.
- Gaseous hydrogen storage cylinders are already commercially available for a variety of applications, but demand is low. Therefore, a market transformation program would help increase demand for fuel cells and hydrogen storage.
- Infrastructure for hydrogen refueling is a concern for hydrogen storage technology manufacturers and it's necessary to increase the efforts to provide an infrastructure and DOE support is recommended.
- This study was aimed at hydrogen storage for fuel cell applications; however, it was revealed that hydrogen storage is also used in other technologies, such as heat exchangers and thermal energy storage materials, that are viable technologies in need of support by DOE to be further developed and integrated in the hydrogen infrastructure.
- It is important to routinely perform TRA/MRA analysis of hydrogen storage technologies in parallel with the ongoing TRA/MRA analysis of fuel cells, to monitor progress and to identify gaps and R&D needs. It is recommended that an ongoing TRA/MRA activity on hydrogen storage technologies is established and that participation in this activity is a requirement for all co-funded demonstration activities.

FY 2012 Publications/Presentations

1. Ewa Rönnebro, Technology and Manufacturing Readiness of Early Market Motive and Non-Motive Hydrogen Storage Technologies for Fuel Cell Applications, Technical Report prepared for U.S. DOE EERE FCTP, PNNL-21473, June 2012.

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