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Manufacturing Readiness Assessment for Fuel Cell Stacks and Systems for the Back-up Power and Material Handling Equipment Emerging Markets

D. Wheeler and M. Ulsh

Technical Report
NREL/TP-560-45406
Revised February 2010

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1. Page 26, section 7.1.1, the last word on the page was changed from Figure 3. to Figure 4.
2. Page 27, first paragraph, first sentence, Figure 3. was changed to Figure 4.
3. Page 28, Figure 4, the actual graph was changed. It was originally the wrong graph.

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Executive Summary

The Department of Energy's Hydrogen, Fuel Cell, and Infrastructure Technologies (HFCIT) Program has successfully supported and guided the advancement of fuel cell and hydrogen technologies for the 80-kW direct hydrogen automotive power system. Importantly, the HFCIT Program-funded cost projections for automotive fuel cell power systems forecast the automotive polymer electrolyte membrane (PEM) fuel cell cost in the range \$60/kW[1] to \$80/kW[2] based on anticipated manufacturing advancements at a proposed production rate of 500,000 80-kW PEM automotive fuel cells per year. Federal cost incentive scenarios do not forecast automotive fuel cell production to reach 500,000 vehicles for at least another ten years[3].

The HFCIT Program supports the creation of a North American domestic manufacturing base and ramping-up of production capacity via its Market Transformation activity. This activity assists federal agencies in transitioning to fuel cell and other renewable energy technologies as required by EPACT 2005 and Executive Order 13423[4]. Expanded federal fuel cell use will create market stimulus to assist manufacturers in the transition to higher volume production methods (thereby reducing unit cost). Market transformation for commercializing PEM fuel cell systems for backup power applications and materials handling equipment (MHE) is strongly supported by the HFCIT Program-commissioned market analyses performed by Battelle[5, 6]. The Federal government's requirements for backup power for FAA applications and MHE at Department of Defense Depots, establishes a demand that can lead this hydrogen-based technology's market transformation.

Transforming the PEM fuel cell market requires transitioning from a prototype to a design-stable, application-ready PEM power system. Manufacturing processes will need to be developed and qualified for high-rate production of durable and reliable PEM fuel cell systems for commercial, real-life backup power, and materials handling applications. A successful market transformation investment will need to minimize the risks inherent in the development of new manufacturing processes for emerging technology.

> **"Investment risk of developing manufacturing capability for hydrogen and fuel cell technologies is high."**
> *-U.S. Department of Energy HFCIT MYPP*

DOE can use Manufacturing Readiness Levels (MRLs) to address the economic and institutional risks associated with a ramp-up in PEM production. According to the HFCIT Program's Multi-Year Research, Development, and Demonstration Plan[7] (MYPP), "Investment risk of developing manufacturing capability for hydrogen and fuel cell technologies is high."

In response to the HFCIT Program's assessment, the National Renewable Energy Laboratory (NREL) has initiated an activity to address the need to understand the current status and associated risk levels of the PEM fuel cell industry. This activity is initially focused on the back-up power and MHE emerging markets. The followings steps detail NREL's methodology.

1. NREL assessed the extensive existing hierarchy of MRLs developed by Department of Defense (DoD)[8] and other Federal entities, and developed a MRL scale adapted to the needs of the HFCIT program and to the status of the fuel cell industry.
2. The MRLs developed by NREL for DOE specifically address the pre-automotive, near-term manufacturing of PEM fuel cell systems. NREL's approach for the DOE PEM MRLs is distinguished from the DoD definition of MRLs by the incorporation of market data, the focus on near-term pre-automotive PEM manufacturing, and the use of industry self-assessment to establish the MRL. While the DoD approach focuses on procurement, the DOE MRL process addresses development of a PEM manufacturing base.
3. NREL, again adapting from the existing DoD formality and adjusting for emerging PEM pre-automotive applications, developed a Manufacturing Readiness Assessment (MRA) with detailed questions to assess the maturity and illuminate the risk factors of a manufacturer's overall manufacturing capability. This detailed assessment was then condensed into a questionnaire form that was used by the manufacturers and NREL to establish the MRL levels of the each manufacturer.
4. Each manufacturer performed a MRA self-assessment using the NREL questionnaire. NREL then visited each manufacturing site, and with the manufacturer, developed consensus MRLs and performed an independent assessment of manufacturing readiness.

The benefits of this ongoing activity to the HFCIT Program, the Market Transformation activity, and to industry, are summarized in Figure ES-1.

Benefits

- A metric for reporting status against HFCIT manufacturing goals
- Information on weaknesses and risk areas in the overall manufacturing capability of the industry, which may reveal opportunities for future manufacturing R&D funding
- Aggregate reporting of industry status, which enables information to be gathered that may otherwise be difficult to obtain, due to Intellectual Property and competitive reasons
- An unbiased and comparative assessment, based on a standard set of metrics, of a manufacturer's entire manufacturing enterprise
- A metric that enables HFCIT Market Transformation decision makers to identify optimal entry ("jump-in") and exit ("jump-out") points for supporting a particular fuel cell market, based on the maturity of the manufacturing capability to address that market
- An anonymous assessment of a manufacturer's capability compared to its peers

Figure ES- 1: Benefits to HFCIT, market transformation, and industry

Manufacturing Readiness Levels

The ten MRLs shown in Table ES-1 demonstrate the increase in manufacturing maturity required to transition to the next higher level. The MRLs range from a "Feasibility Assessment" to "Full Rate Production Demonstrated." The MRL definitions are more stringent at the higher levels, reflecting the increased complexity of the manufacturing requirements during the transition to Full Rate Production (FRP).

The level of production defined as FRP, which is the level of production required to support a mature market, is product and application specific. For FAA tower emergency backup power and forklift truck PEM power systems, the FRPs are 1,700 units/year and ~5,000 units/year, respectively. These values are based on the HFCIT Program Market Analyses conducted by Battelle[5,6]. At MRL – 7, Low Rate Initial Production (LRIP) is defined as the level of production of PEM fuel cell systems or stacks that supports market entry. LRIP is also product and application specific. Based on fuel cell industry interviews and the most recent market information generated by Battelle and inputs from industry, NREL defines LRIP as 1,000 units / year.

The Battelle analysis for FAA tower emergency backup power assumes an instantaneous 75% penetration into the replacement market. This level of penetration is considered to be high based on industry input. Industry anticipates the year one market entry to be several hundred units growing to 1,000 units per year over a two year period, i.e. growing to the LRIP value. The industry production numbers are consistent with present purchases.

For the forklift truck applications, Battelle identified the Defense Logistic Agency and the US Postal Service as early adaptors of this technology with initial replacement purchases of 472 units per year. Penetration into the forklift truck replacement market was 20% for all but the Class 2, narrow-aisle, high-reach forklifts, which have a 5% penetration into the replacement market. The market entry of 1,000 units per year for LRIP was confirmed during interviews with forklift PEM power systems manufacturers.

Table ES -1: Manufacturing Readiness Levels[8]

MRL - 1	Manufacturing Feasibility Assessed
MRL - 2	Manufacturing Concepts Defined
MRL - 3	Manufacturing Concepts Developed
MRL - 4	Laboratory Manufacturing Process Demonstration
MRL - 5	Manufacturing Process Development
MRL - 6	Critical Manufacturing Process Prototyped
MRL - 7	Prototype Manufacturing System
MRL - 8	Manufacturing Process Maturity Demonstration
MRL - 9	Manufacturing Processes Proven
MRL - 10	Full Rate Production demonstrated and lean production practices in place

Risk Elements

The MRLs are further broken down into risk elements, which identify nine specific risk areas to be assessed as the manufacturing process matures. The risk elements are consistent for all the MRLs, but the assessment questions of the risk elements change as a more sophisticated manufacturing capability, and higher MRL ranking, is achieved. The risk elements are:

1. Technology & the Industrial Base
2. Design
3. Materials
4. Cost & Funding
5. Process Capability and Control

6. Quality Management
7. Manufacturing Personnel
8. Facilities
9. Manufacturing Planning, Scheduling, and Control

The NREL-developed MRA process is built on the MRLs and their associated risk elements. The MRA was condensed into a family of questions for each of the nine risk elements to facilitate ease of response by industry. NREL worked with the PEM manufacturers Hydrogenics, Inc., Nuvera, Inc., Plug Power, Inc., and Protonex, Inc. to validate the MRA. These four companies conducted MRA self-assessments using the NREL questionnaire applied to the following three manufacturing categories:

1. Emergency backup power PEM power systems and Auxiliary Power Units (APUs): Hydrogenics, Plug Power, & Protonex
2. Forklift Truck PEM power systems: - Hydrogenics, Nuvera, & Plug Power
3. PEM Cell Stack Manufacture: - Hydrogenics, Nuvera, Plug Power, & Protonex

MRA of Emergency Backup Power & APUs

The aggregate and consensus MRA self-assessment data for backup power & APUs are graphically represented in Figure ES-2.

The PEM emergency backup power & APU industry has not achieved LRIP. The lowest rated risk element is "Personnel," which includes preparing training programs for manufacturing, preparing the trainers, developing the instruction and skill of manufacturing personnel, and verifying their skill during pilot line production. The ranking range for Personnel is MRL – 4 to MRL – 6. The MRL - 4 rating of the risk element Personnel reflects the emphasis of the industry on development and demonstration of a prototype design. The transition from laboratory prototype to pilot line production will require personnel training. The Design risk element is rated at LRIP (High rating) or ready for LRIP (Low rating), signifying there are either no design changes or the design changes have decreased and are minimal. By validating the design of emergency backup power and APU systems, the market demand becomes the driving force for increasing manufacturing readiness.

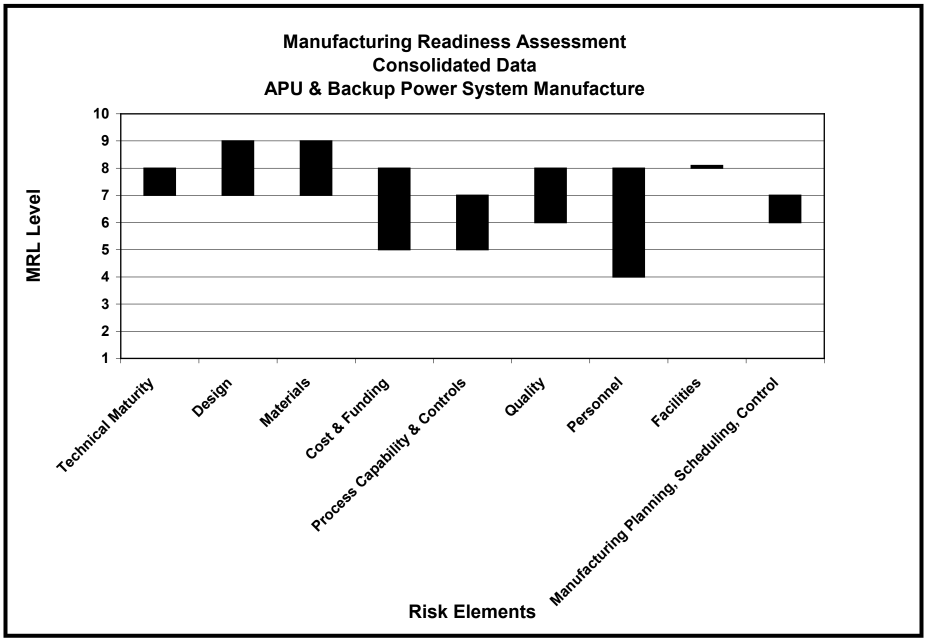

Figure ES-2: Aggregate consensus MRLs for PEM power systems for emergency backup power & APUs

MRA of Forklift Truck Power Systems

The aggregate and consensus MRA self-assessment data for the forklift power systems are graphically represented in Figure ES-3.

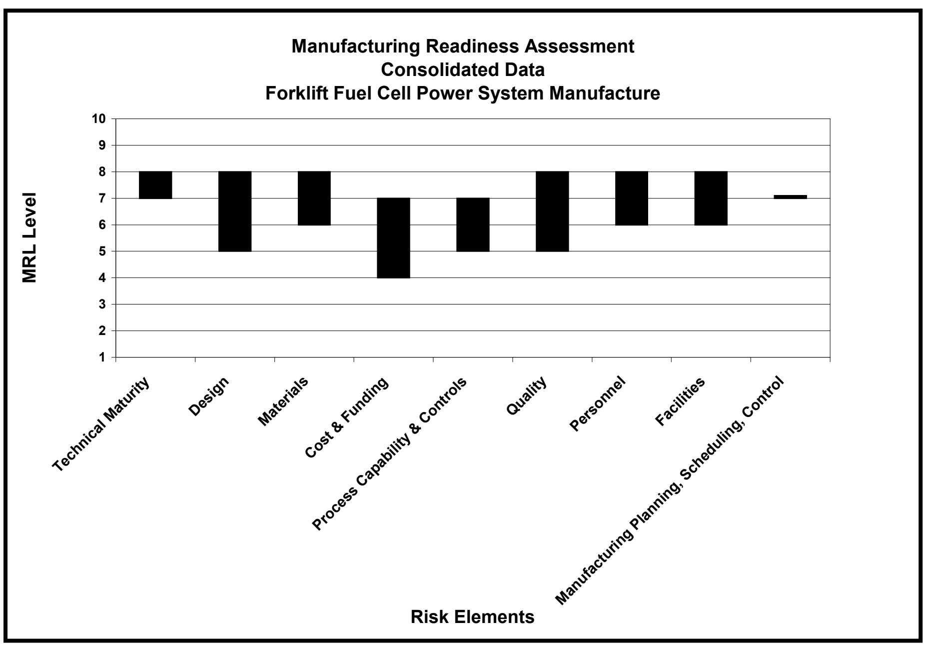

Figure ES -3: Aggregate consensus MRLs for PEM power systems for forklift trucks

The manufacturing readiness based on the aggregate data indicates that the PEM power system industry for forklift trucks has a broad range of risk element rankings. The lowest ranked risk element is Cost & Funding, although its ranking covers a span of three MRLs: MRL – 4 to MRL – 7.

MRA of Cell Stack Manufacture

The aggregate and consensus MRA self-assessment data for the cell stack manufacture are graphically represented in Figure ES-4.

The risk element Cost & Funding covers the range MRL – 5 to MRL – 8. The companies with the lower rating emphasized the development and demonstration of the prototype design and are only beginning to implement cost reduction programs. Some of the risk-element criteria have been met; e.g. make / buy programs have been initiated, while other risk elements such as cost controls on the suppliers and subcontractors have not been achieved. The poor cost control by the suppliers may be resolved as increasing production volumes provide leverage.

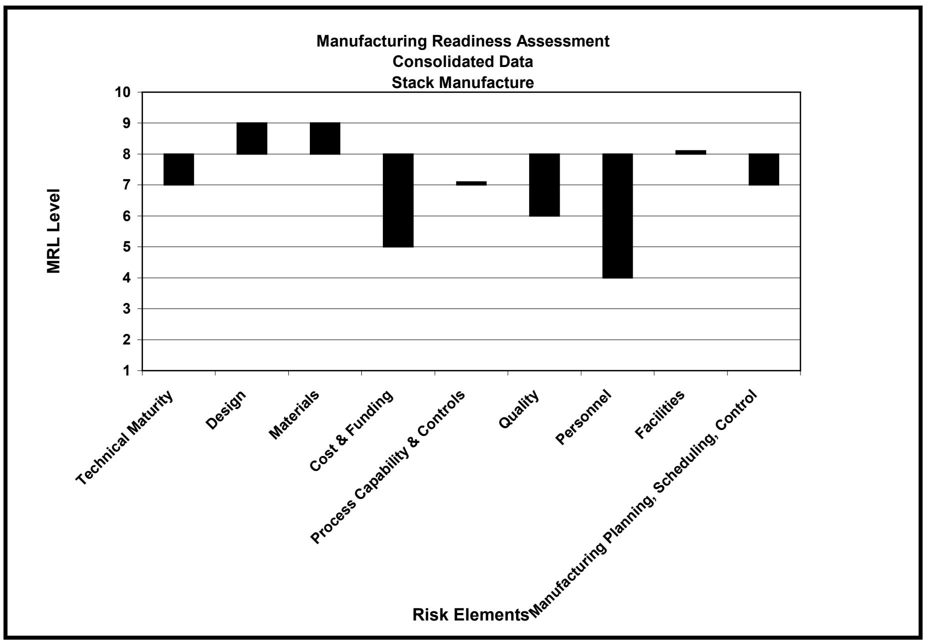

Figure ES-4: Aggregate consensus MRLs for PEM cell stack manufacturing

The risk element Quality covers the range MRL – 6 to MRL - 8 and identifies that final quality and reliability levels for some stack manufacturers have not been established. In addition, the quality and reliability requirements have not been set for the suppliers and subcontractors. The risk element Quality can be easily elevated to MRL – 7 ("ready for LRIP") because the ranking of the two risk elements Design and Materials are both at MRL – 8 ("operating at LRIP") and further developmental activity for these two high ranking elements has been completed. The design and materials are fixed.

Conclusions

The NREL-developed MRA brought into focus the manufacturing risks associated with achieving LRIP of 1,000 PEM systems per year. Four important conclusions resulted from the companies' self-assessments and NREL's assessment of the manufacturing status:

1. Based on the reported company time-study assessments, PEM companies are confident their manufacturing approaches can achieve LRIP of 1,000 forklift truck PEM power systems per year. The companies are not at the 1,000 unit LRIP today for forklift PEM power systems. Based on current market demand, actual production rates are currently in the range of 200-300 units per year.
2. Based on the reported company time-study assessments, PEM companies are confident their manufacturing approaches can achieve LRIP of 1,000 power systems per year for Emergency Backup Power & APUs. The companies are not at the 1,000 unit LRIP today. Based on current market demand, actual production rates are currently in the range of 200-300 units per year.
3. The Manufacturing Readiness for cell stacks is the most advanced of the three manufacturing capabilities assessed. There was a high level of risk for stack development for staffing and training of production personnel. Importantly, costs of the cell stack also represent a risk. Because the cell stack is an integral and dominating component of PEM systems, resolving these two risk issues, Personnel and Cost, is critical for companies to achieve FRP.
4. The risk elements Cost & Funding, Personnel, and Quality had lower rankings for forklift truck, emergency backup power, and APU applications. NREL considers these low ranking risk elements to be representative of the transition from PEM prototype development to a stable, commercial PEM system design. The establishment of a stable PEM design changes the emphasis from demonstration to high rate quality production of a cost competitive PEM system by trained personnel.

Recommendations

Based on the MRAs performed with the four manufacturers active in the back-up power and MHE emerging markets for PEM fuel cells, NREL provides the following recommendations:

Recommendations Based on the Manufacturing Readiness Assessments

- Two risk elements with poor rankings identified by the MRAs of the three applications (forklift trucks, emergency backup power and APUs), are Cost & Funding and Personnel. The major barrier for both of these risk elements is market demand.
  - Increasing the market demand will provide the impetus for fuel cell manufacturers to increase production staff, implement training programs, and resolve and improve the ranking of the Personnel risk element. **Market transformation programs that identify mission structure applications for fuel cells are designed to increase market demand and are recommended.**

- The present platinum content combined with the cost of platinum catalyst causes a high initial purchase price for PEM fuel cells. **Research and development support to lower the catalyst content and drive down the initial purchase price of fuel cells is recommended.**

- The risk element Quality is the third common problem area identified by the MRAs. The cell stack and fuel cell system conditioning process is costly, time consuming, and requires expensive testing equipment. In-line, continuous quality control measurements are rare and not fully developed for the assembly of cell stacks and fuel cell systems, as well as for the production of cell components. **Quality control methodology for stack component inspection and reduction of cell stack and fuel cell system conditioning time are a recommended area for DOE support.**

Programmatic Recommendations

- The MRA provides an assessment of the progress of a manufacturer toward LRIP and FRP for a given market segment, using a standard methodology that can lead to comparative and agglomerate analyses of the industry. The evaluation of LRIP for an emerging market and the assessment of a manufacturer's ability to produce at LRIP can be used as "jump-in"/ "jump-out" criteria for Market Transformation decision makers. **An ongoing MRL assessment activity should be established to support the HFCIT Market Transformation activity. Participation in this activity should be a requirement for all co-funded demonstration activities, so that unbiased, comparative assessments can be made.**
- **The MRA of Ballard cell stacks for the backup power and MHE markets is an important metric of fuel cell stack manufacturing, and should be included as a follow-on activity to this report if possible.**
- Manufacturing processes for bipolar plates and membrane-electrode-assembly (MEA) components are critical, time consuming, and costly. Manufacturing rates for the MEAs and bipolar plates need to be up to 25 times greater than stack manufacturing rates. **The manufacturing readiness of the cell components is critical to the commercialization of PEM fuel cells and should be assessed as a follow-on activity of this report.**
- Assessing automotive cell component and stack manufacture introduces a new level of quality and cost control. Over 200 million MEAs would need to be manufactured annually or 400 MEAs per minute for automotive applications. **The MRA of automotive cell component and cell stack manufacturing is critical to forecasting the entry of PEM fuel cell powered vehicles.**

Contents

Acronyms

APC	American Power Conversion
APUs	Auxiliary Power Units
BOP	Balance of plant
DLA	Defense Logistics Agency
DoD	Department of Defense
DOE	Department of Energy
EPACT	Energy Policy Act
FAA	Federal Aviation Association
FRP	Full Rate Production
HFCIT	Hydrogen, Fuel Cell, and Infrastructure Technologies
IPT	Integrated Product Teams
JIT	"Just In Time"
LRIP	Low Rate Initial Production
MRA	Manufacturing Readiness Assessment
MRLs	Manufacturing Readiness Levels
MHE	Materials Handling Equipment
MEA	Membrane Electrode Assembly

MYPP	Multi-Year Research, Development, and Demonstration Plan
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PEM	Polymer Electrolyte Membrane
R&D	Research & Development
TRLs	Technology Readiness Levels
VRLA	Valve Regulated Lead Acid

1 Introduction

The Department of Energy's (DOE's) Hydrogen, Fuel Cell, and Infrastructure Technologies (HFCIT) Program has successfully supported and guided the advancement of fuel cell and hydrogen technologies for the 80-kW direct hydrogen automotive power system. Ahead of 2008 forecasts, the HFCIT Program reported surpassing the 5,000 hour membrane durability target for 2010[9]. Importantly, the 2008 HFCIT Program-funded cost projections for automotive fuel cell power systems forecast automotive polymer electrolyte membrane (PEM) fuel cell costs in the range \$60/kW[1] to \$80[2]/kW based on anticipated manufacturing advancements at a proposed production rate of 500,000 80-kW PEM automotive fuel cell systems per year. Today, the projected PEM cost at high volume production is approaching the HFCIT Program target for 2010; \$45/kW. However, due to the required production capacities and the long-term commitment necessary to ensure the logical coordinated roll-out of a hydrogen-fueling infrastructure and fuel cell vehicles, a large-scale market is still a number of years away. Even the most favorable federal cost incentive scenarios do not project manufacturing production to reach 500,000 vehicles for over ten years.[3]

The success of the HFCIT Program research and development efforts will accelerate the PEM fuel cell transition from laboratory demonstration to *pre-automotive* applications. As Greene[10] succinctly concludes, "the non-automotive fuel cell industry in North America appears to be at a critical point" where industry can begin commercialization of PEM fuel cells for backup power applications and materials handling equipment. The applications identified by Greene[10] reference the HFCIT-sponsored market analyses of Mahadevan et al.[5,6] of Battelle. Mahadevan concludes that a federal requirement for PEM use in backup power and materials handling equipment (MHE) can lead the market transformation for PEM fuel cell systems. Such federal government requirements would increase production from the current industry-wide production of hundreds of PEM systems per year to several thousands of PEM systems per year. Greene[10] and Mahadevan et al[5, 6] acknowledge that manufacturing processes will need to be developed and qualified to provide reliable PEM fuel cell systems in the backup power and MHE applications at production rates of several thousands of PEM systems per year.

The HFCIT Program is supporting emerging market opportunities for pre-automotive fuel cell applications. This support is based on an understanding of the long-term development needs for fuel cell vehicles to become an economically viable solution to the environmental issues associated with high carbon dioxide producing fuels[11]. The HFCIT Program supports the creation of a North American domestic manufacturing base and ramping-up of production capacity. HFCIT's support is provided by the Program's Market Transformation activity, which seeks to create market stimulus to assist manufacturers in transitioning to higher volume production methods (and the resulting reduced unit cost). The Market Transformation activities assist federal agencies in transitioning to fuel cell and other renewable energy technologies to meet EPACT 2005 and Executive Order requirements[4]. Figure 1 illustrates the goals of the Market Transformation activity via the well-known economy of scale curve for fuel cells.

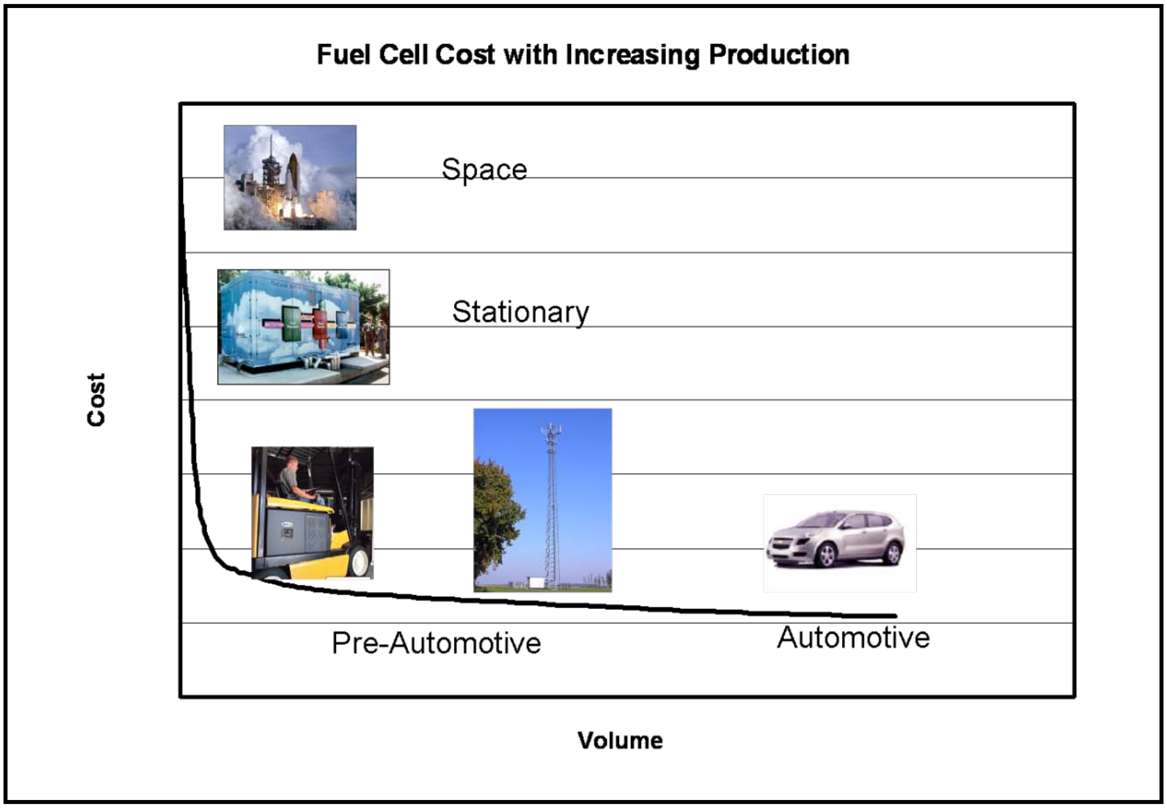

Figure 1: Schematic of fuel cell cost increasing with volume

Manufacturing Readiness Levels (MRLs) address the economic and institutional risks that are associated with a ramp-up in PEM production and have been identified in the HFCIT Program Multi-Year Research, Development, and Demonstration Plan[7] (MYPP). According to the MYPP, "Investment risk of developing manufacturing capability for hydrogen and fuel cell technologies is high."

> **"Investment risk of developing manufacturing capability for hydrogen and fuel cell technologies is high."**
> *- U.S. Department of Energy HFCIT MYPP*

The MRLs are standard metrics for measuring the risks associated with manufacturing a commercial product. The Manufacturing Readiness Assessment (MRA) is a process that uses MRLs to concisely appraise the readiness of an industry to deliver a mature product for commercial applications. The MRA supports Market Transformation by reducing risk for the transition from the laboratory to industrial, real world applications. The MRA is used to gauge the status of production processes and production costs of an emerging technology using a standard set of measures that include the critical metrics required for a technology to move to the market. The MRA enables HFCIT program managers to make informed funding decisions by quantifying the manufacturing maturity and minimizing the risk associated with introducing new PEM fuel cell technology into the market place.

The MRLs developed by the National Renewable Energy Laboratory (NREL) for DOE specifically address the pre-automotive, near-term manufacturing of PEM fuel cell systems. NREL's approach for the DOE PEM MRLs is distinguished from the Department of Defense (DoD) definition of MRLs and the DoD MRA process by the incorporation of market data, the focus on near-term pre-automotive PEM manufacturing, and the use of industry self-assessment to establish the MRL. While the DoD approach focuses on government acquisition, the DOE MRL process addresses the development of a PEM fuel cell manufacturing base in a consumer-driven market.

1.1 About this Report

The purpose of this report is to discuss an assessment of MRLs of fuel cell manufacturers and the value of this information to DOE and industry. The report will provide information gathered recently by NREL on the readiness of selected fuel cell manufacturers to produce at rates that will support emerging fuel cell markets, which, ultimately, could provide the economic stability to make future improvements in manufacturing capacity that will lead to the viability of fuel cell vehicles.

The report is composed of the following sections:

Section 1 will introduce the background and need for an ongoing assessment of MRLs.

Section 2 will describe NREL's activity in preparing for this assessment and NREL's process for MRL assessment.

Section 3 will introduce the concept and uses of MRLs.

Section 4 will explain the MRA and the tools developed to perform the MRA.

Section 5 will use the Battelle reports[5,6] to show the production levels required for emerging fuel cell markets, and how these levels relate to MRLs.

Section 6 will introduce the fuel cell manufacturers active in the back-up power and MHE markets.

Section 7 will provide the manufacturer's MRL self-assessments and NREL's assessment of manufacturing readiness for backup power, APU, and forklift truck PEM power systems.

Section 8 will provide the manufacturer's MRL self-assessments and NREL's assessment of manufacturing readiness for PEM cell stacks.

Section 9 will present key barriers to achieving necessary production rates identified during the MRAs.

Section 10 will present conclusions.

Section 11 will present recommendations.

2 NREL's MRL Activity

NREL supports the DOE Hydrogen Program's HFCIT Program in the areas of manufacturing assessment, manufacturing research, and development (R&D), and market transformation. In 2005, NREL and the National Institute of Standards and Technology (NIST) assisted the DOE and industry in developing the DOE Roadmap on Manufacturing R&D for the Hydrogen Economy.[12] This roadmap documented the barriers to high volume production of fuel cells and led toward HFCIT's current activities in manufacturing R&D. Then, in 2007, NREL, with substantial input from industry interviews, published an analysis of the manufacturing status of the U.S. PEM fuel cell industry titled, "2007 Status of Manufacturing: Polymer Electrolyte Membrane (PEM) Fuel Cells."[13] NREL's activities in these areas supported the HFCIT Program's progress toward meeting their milestones. The HFCIT milestones supported by these works are:

- 2010: Complete development of standards for metrology of PEM fuel cells.
- 2011: Demonstrate pilot scale, high volume manufacturing processes for high-pressure composite tanks.
- 2012: Develop continuous in-line measurement for MEA fabrication.
- 2012: Demonstrate pilot scale processes for manufacturing bipolar plates.
- 2013: Establish models to predict the effect of manufacturing variations on MEA performance.
- 2013: Demonstrate pilot scale processes for assembling stacks.

2.1 Manufacturing Readiness Levels, Technology Readiness Levels, and the Manufacturing Readiness Assessment

NREL is supporting the HFCIT milestones by developing a risk-based measure of an industry's ability to transition from R&D activities to commercialization and delivery of a mature product with established performance and durability characteristics. NREL developed MRLs for DOE that would define the status of PEM pre-automotive manufacturing. The DOE MRLs are metrics to gauge the progress of the PEM industry in its market transformation from R&D to commercialization. The DOE MRLs were designed to address emerging manufacturing processes that would be the precursors to large scale manufacturing of PEM fuel cell systems for the light vehicle market.

The NREL approach to the MRL development activity followed two parallel paths; shown graphically in Figure 2. Path 1 combined the established MRL activities of the DoD[8] with the stage/gate process used by industry[14] and the Technology Readiness Levels (TRLs) developed for PEM systems by the DOE.[15] Path 1 of the effort developed definitions of risk associated with the transition to PEM manufacturing. Path 2 combined the results of the DOE-funded PEM market assessment[5, 6] with market information from industry interviews. The Path 2 process was augmented with the HFCIT Program's identification of manufacturing gaps[13]. The Path 2 approach developed the Near-Term Low Rate Initial Production definition.

Integrating the results of the Path 1 and Path 2 activities defined the Near-Term PEM MRL definitions, as shown in Figure 2. The near-term MRLs form the basis for the MRA. An important feature of the NREL-developed MRA is the concept of industry self-assessment using the DOE PEM MRLs. The self-assessment MRA by industry and the MRA conducted by NREL highlight the areas of manufacturing development that need growth and assistance.

NREL's approach for the DOE PEM MRLs is distinguished from the DoD definition of MRLs and the DoD MRA process by the incorporation of market data, the focus on near-term pre-automotive PEM manufacturing, and the use of industry self-assessment to establish the MRLs. While the DoD approach focuses on procurement, the DOE PEM MRL process addresses development of a PEM manufacturing base.

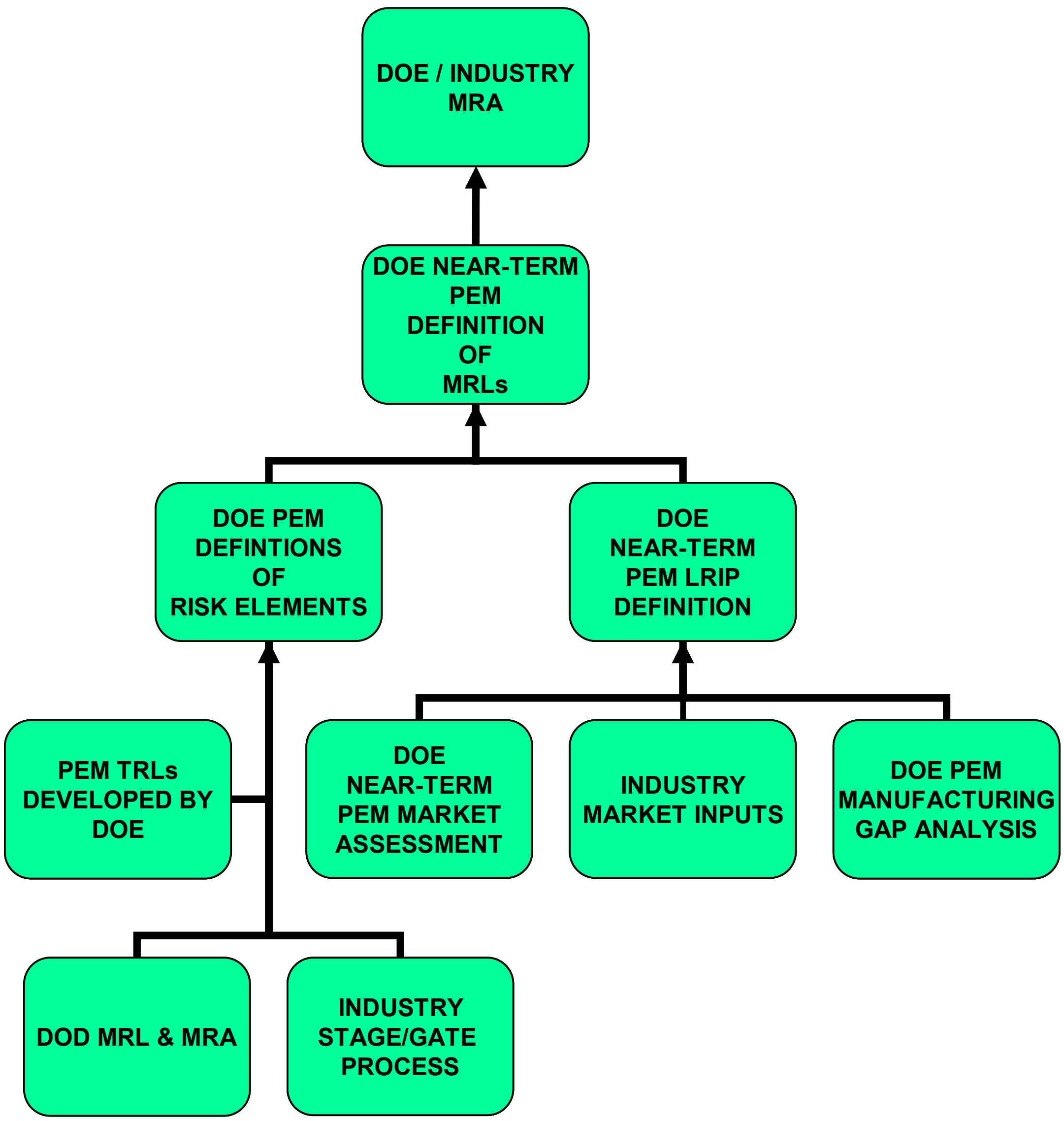

Figure 2: Process used by NREL to develop Manufacturing Readiness Levels for DOE near-term PEM fuel cells

The NREL-developed MRLs evaluate a broad range of manufacturing, planning, personnel, quality, and financial aspects of a supplier's production capability. A key function of MRLs is to assess industry's ability to manufacture at two production rates whose value is defined by the specific market being addressed by the product. These two production rates are:

Low Rate Initial Production (LRIP): This is the first stage of production and represents a transition from the production of a one-of-a-kind design to production of a product with established, fixed design manufacturing processes that are repeatable, have a high yield, have controlled costs, and have a high level of quality control. In many cases, LRIP is the manufacturing level associated with pilot plant production.

Full Rate Production (FRP): In this stage of production, manufactured systems and components fulfill all engineering, performance, quality, and reliability requirements. Production rate, production costs, and material costs fulfill all cost goals. System design, component designs, and manufacturing processes are fixed and under "change control." Lean manufacturing processes are established and continuous process improvement procedures have been implemented. Manufacturing is in a sustainment phase with products meeting the requirements of a maturing market.

The ability of MRLs to assess the readiness of the entire manufacturing enterprise relative to the LRIP and FRP production levels makes the MRL an extremely valuable tool that benefits the HFCIT's activities, including market transformation. Section 5 provides an assessment of LRIP for the back-up power and MHE markets.

Manufacturing readiness closely parallels technology readiness. A general requirement of MRLs is that they cannot be more advanced than Technology Readiness Levels (TRLs) since a key element for manufacturing readiness is the establishment of a fixed design and elimination of design changes. To achieve a fixed design, the technology development process must reach a mature level. The close association of MRLs with TRLs requires that standard definitions be developed for the MRLs and TRLs. The dependence of MRLs on TRLs is properly achieved when the TRLs define a systematic set of metrics that calibrate the maturity of the technology.

The MRA is the process for assessing the risk and maturity of a company's manufacturing capability. The MRA determines the status of manufacturing toward achieving milestone production rates. It defines and facilitates the management of risk and calibrates the status of a manufacturing process using the standards established as MRLs. The end goal of an MRA is to define activities by either identifying weaknesses in the manufacturing process or concurring with the transition to LRIP or, for advanced manufacturing efforts, the transition to FRP.

2.2 NREL Activity and Benefits of the MRL Assessment Process

In order to evaluate MRLs for fuel cell markets, NREL reviewed existing resources for MRLs, TRLs, and the MRA processes to assess their viability for meeting the needs of the HFCIT program. NREL determined the DoD MRLs and MRA process covered a very broad range of equipment and weapons acquisition with early deployment of systems, and the process was so broad that specificity to PEM manufacturing was difficult to assign. Additionally, the DoD assessment process did not use independent company-based assessments.

TRLs specific to PEM fuel cell systems were previously developed by the HFCIT Program. These TRLs were readily adapted to the MRLs developed by NREL. Section 3 details the MRLs developed by NREL for fuel cell emerging markets. Section 4 describes the process and tools NREL developed for the MRA. The HFCIT fuel cell TRLs are given in Appendix A.

MRLs are reporting metrics that identify the strengths and weaknesses of the manufacturing capability of the industry. A two-stage MRA was developed by NREL to assess the PEM manufacturing industry. Industry conducted their own MRA using the MRLs defined by the NREL process for the first stage of the assessment. NREL conducted an independent assessment by interviewing industry in the second stage of the assessment. The second stage required agreements with each manufacturer for full review and concurrence with the MRA results, and total anonymity (other than the fact that they were visited). The second stage agreement opened the door for information which may otherwise have been difficult for HFCIT to obtain because of Intellectual Property and the competitive nature of the PEM fuel cell business. Most importantly, the two-stage assessment process yields an unbiased and comparative assessment of manufacturing readiness – not only of production capacity, but a broad review of the systems that need to be in place to support manufacturing. A critical feature of the two-stage assessment is the standard set of metrics employed by both industry and NREL; these standard metrics normalize the data when reviewing multiple companies.

Having established tools specific to fuel cells, NREL then performed MRAs with fuel cell manufacturers active in the back-up power and materials handling equipment fuel cell markets. NREL's approach provided implicit feedback on the quality of the MRLs because of the close industry interaction. The process for assessing MRLs had three steps:

1. Manufacturers evaluated the NREL-developed MRLs and used them to determine their position on the MRL scale.
2. NREL visited the manufacturers to obtain consensus on the MRLs and to develop an independent assessment of manufacturing readiness.
    - NREL provided the manufacturers with a final version of the MRL scores and its independent assessment.
    - The manufacturers provided comments and corrections, and approved the information for submission to DOE.
3. NREL provided the HFCIT Program with a final report summarizing the MRAs in a manner that maintains the anonymity of data specific to each individual manufacturer.

Benefits

- A metric for reporting status against HFCIT manufacturing goals
- Information on weaknesses and risk areas in the overall manufacturing capability of the industry, which may reveal opportunities for future manufacturing R&D funding
- Aggregate reporting of industry status, which enables information to be gathered that may otherwise be difficult to obtain, due to Intellectual Property and competitive reasons
- An unbiased and comparative assessment, based on a standard set of metrics, of a manufacturer's entire manufacturing enterprise
- A metric that enables HFCIT Market Transformation decision makers to identify optimal entry ("jump-in") and exit ("jump-out") points for supporting a particular fuel cell market, based on the maturity of the manufacturing capability to address that market
- An anonymous assessment of a manufacturer's capability compared to its peers

The discussion above highlights many of the benefits of the NREL MRA process to DOE. Of key importance is the development of tools and methods that support the goals of the Market Transformation activity. In particular, an ongoing MRL assessment activity provides information that can be used as a "jump-in"/ "jump-out" metric[16] for market transformation funding. For example, an emerging market with a low market entry volume would waste market transformation time and funding by supporting a manufacturing effort for a market that is too immature. On the other hand, as a market matures, manufacturers will be motivated to increase capacity based on normal market demand, and thus market transformation support would be superfluous. Thus, an optimal range of manufacturing readiness, for a particular emerging market, can be identified using MRAs and market analysis. The bounds of this optimal range can define jump-in and jump-out points for market transformation support. An understanding of what LRIP is for a certain market, and whether a manufacturer is at an MRL that supports LRIP, is critical for defining the jump-in and jump out points for market transformation.

Beyond DOE, the MRA provides industry with an unbiased, independent third party assessment of manufacturing strengths and weaknesses. The MRA defines a manufacturer's capability relative to industry peers, and can highlight manufacturing deficiencies that might benefit from R&D funding.

3 Manufacturing Readiness Levels

As discussed above, MRLs are an approach to a risk-based assessment of the progress toward manufacturing goals. The MRLs are the underlying structure that binds a MRA to product commercialization and market transformation. The MRL metrics reinforce planning for the HFCIT Program Manufacturing R&D and Market Transformation activities. The role of MRL assessment is graphically represented in Figure 3[17].

The MRL scales are made up of incremental steps that provide the criteria for judging the progress of a manufacturing R&D program toward full-fledged manufacturing. NREL prepared an MRL scale for evaluating PEM fuel cell stack and system manufacturing processes. The MRLs were focused on the pre-automotive early-adaptor PEM fuel cell back-up power (including auxiliary power units) and motive power for MHE, specifically forklift trucks. The primary definitions for the manufacturing readiness levels are given in Table 1.

Figure 3: Role of Manufacturing Readiness Levels in transitioning to full rate production

Table 1: Manufacturing Readiness Levels[8]	
MRL	**Definitions**
1	**Manufacturing Feasibility Assessed –** Top level assessment of feasibility based on technical concept and laboratory data.
2	**Manufacturing Concepts Defined** – Initiate demonstration of feasibility of producing a prototype system or component.
3	**Manufacturing Concepts Developed –** Manufacturing concepts identified and based on laboratory studies.
4	**Laboratory Manufacturing Process Demonstration**. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Targets set for cost as an independent variable, and initial cost drivers identified.
5	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.
6	**Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.
7	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production. Manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Table 1: Manufacturing Readiness Levels[8]	
MRL	**Definitions**
8	**Manufacturing Process Maturity Demonstration**. Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).
9	**Manufacturing Processes Proven.** Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to 6-sigma or appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met). Actual cost model developed for FRP environment, with impact of continuous improvement. Full rate process control concepts under development. Training and budget plans in place for transition to full rate production.
10	**Full Rate Production demonstrated and lean production practices in place** The system, component or item is in full rate production. Technologies have matured to at least TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. System, components, or items are in full rate production and meet all engineering, performance, quality, and reliability requirements. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

Each MRL is further broken down into risk elements, which identify nine specific risk areas to be assessed for passage from one MRL to the next. The risk elements are consistent for all the MRLs, but the assessment questions for each of the risk elements demand a more sophisticated manufacturing capability as the MRL advances.

The risk elements are given below:

1. Technology & the Industrial Base: Analysis of the capabilities to support the design, development, and production of the emerging technology.
2. Design: Requires an analysis system design to meet user requirements and incorporation of design for manufacturing rigor.

3. Materials: Requires analyses of the risks associated with materials availability, component availability, and sub-system availability.
4. Cost & Funding: Requires analyses of the current cost and full scale production cost and development of pathways to meet manufacturing cost goals.
5. Process Capability and Control: Requires an analysis of the risk that the manufacturing processes may not be sufficient to produce system at required cost.
6. Quality Management: Requires identification of pathways to control quality, and foster continuous quality improvement.
7. Manufacturing Personnel: Requires the assessment of the required skills, training requirements, and availability of personnel to support the manufacturing effort.
8. Facilities: Requires an analysis of the facility capabilities and identification of facility needs to support manufacturing efforts.
9. Manufacturing Planning, Scheduling, and Control: Requires development of planning schedules and control of scheduling needs to meet cost and production goals.

4 Manufacturing Readiness Assessment

The MRA evaluates and grasps the status of the overall manufacturing enterprise and assigns a MRL. The MRA delineates the maturity of the manufacturing process, the maturity of the system or component design, the maturity or readiness of the manufacturer's personnel and facilities, and the readiness of the manufacturer to provide a quality product that fulfills the commercial requirements. The metrics for the assessment are contained in the MRLs and the risks associated with a manufacturing process are contained in the risk elements.

NREL developed the two-stage MRA tool for assessing the MRLs of PEM fuel cell stack and systems manufacturing processes. The tool incorporates a series of interviewer questions based on the nine risk elements previously defined. The MRA tool questions are designed to permit the manufacturer to confirm their status relative to the risk elements. A negative answer establishes the MRL relative to a specific risk element. The lowest MRL identified relative to the nine risk elements conservatively defines the manufacturing readiness of the process and concurrently identifies the highest risk for the manufacturer.

The second stage of the MRA is an independent assessment of the manufacturing process using the same metrics used by the manufacturer and is a method of corroborating the assessment by the manufacturer. The independent assessment involves interviews with company representatives and inspection of the manufacturing facilities. The NREL MRA tool incorporates an early dialog between manufacturer, independent assessor (NREL), and HFCIT. The NREL MRA tool requires the manufacturer and the independent assessor to reach a consensus MRL. Sections 7 and 8 present the data from both the self assessments and the independent assessments for back-up power and MHE fuel cell systems and stacks.

The MRA questions used by the manufacturer and by the independent assessor to ascertain if the manufacturing process has reached MRL – 4 is provided in Table 2. The MRA questions are in the form of a worksheet with the nine risk elements and their evaluation questions. The MRA questions for MRLs 5 through 10 are provided in Appendix B.

Table 2 Manufacturing Readiness Level 4 Worksheet [8]

Laboratory Manufacturing Process Demonstration. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Cost as an independent variable targets set and initial cost drivers identified.	
Application PEM Stacks and PEM Systems	
	Status
Risk Element - 1 **Technology and Industrial Base**	
Technical Maturity	
Program has achieved TRL = 4.	
Manufacturing technology risks / barriers are identified.	
Parts and components in pre-production form exist.	
Scalable technology prototypes have been produced in laboratory.	
Is there industrial support and capabilities for program?	
Have subcontractors been identified?	
Have the long-lead items been identified?	
Risk Element - 2 **Design**	
Does the engineering plan support manufacturing of evolving design?	
Integrated Product Teams (IPT) have been formed and include manufacturing and engineering.	
Is there an **"Engineering Change Process?"**	
Is there a configuration management process with subcontractors?	
Will component testing be completed for "changed" processes?	
Design for Manufacturing	
Have producibility engineering trade studies been initiated?	
Are the component and hardware requirements established?	

Laboratory Manufacturing Process Demonstration. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Cost as an independent variable targets set and initial cost drivers identified.	
Application PEM Stacks and PEM Systems	
	Status
Risk Element - 2 **Design continued**	
Does manufacturing plan evaluate the producibility of system and components?	
System design low risk for manufacturing.	
IPT guided by "Design to Cost" criteria.	
Tooling design plan	
Special tooling and test equipment required.	
Funding requirements for special tooling been evaluated.	
Risk Element - 3 **Materials**	
Materials Standardization	
Material standardization plan under development.	
Material Availability & Handling	
Exotic / high cost materials identified and addressed.	
Initiate evaluation of material lead times and capacity issues.	
Initiate material control and inventory control processes.	
Environmental issues with materials identified.	
Risk Element - 4 **Cost and Funding**	
Design to Cost	
The total system cost goals are available to the Integrated Production Team and used to guide the system design.	

Laboratory Manufacturing Process Demonstration. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Cost as an independent variable targets set and initial cost drivers identified.	
Application PEM Stacks and PEM Systems	
	Status
Risk Element - 4 **Cost and Funding continued**	
Cost Drivers	
Manufacturing cost drivers are identified.	
Individual identified who is responsible for monitoring costs.	
Initiate the analysis of the non-recurring capital and engineering costs.	
Evaluate subcontractors and suppliers cost control practices.	
Cost Reduction Plan	
Cost reduction plan in place.	
Risk Element - 5 **Process Capability and Control**	
Manufacturing Processes	
Key manufacturing processes been identified.	
The manufacturing State-of-the-Art is identified and manufacturing processes that need to be developed identified.	
Have key manufacturing processes been assessed in the laboratory?	
Alternative manufacturing processes have been identified for critical technologies.	
Pilot line build initiated.	

Laboratory Manufacturing Process Demonstration. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Cost as an independent variable targets set and initial cost drivers identified.	
Application PEM Stacks and PEM Systems	
	Status
Risk Element - 6 **Quality**	
Quality Strategy	
Initiate continuous process improvement program.	
Metrology program is in place.	
Sigma level analyses and variability analysis initiated.	
Supply Chain Quality	
How is subcontractor quality verified?	
Risk Element - 7 **Personnel**	
Specialty Skills & Training	
Personnel consistent with specialty skill requirements are in place.	
Training program necessary for specialty skills is in place.	
Training programs are in place for Process Control and Quality.	
Risk Element - 8 **Facilities**	
Facility Requirements	
Facilities are available consistent with proposed Low Rate Initial Production levels or are build plans in place.	
Facility personnel members are part of the Integrated Product Team?	
Non-recurring costs associated with facility requirements are documented.	

Laboratory Manufacturing Process Demonstration. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Cost as an independent variable targets set and initial cost drivers identified.	
Application PEM Stacks and PEM Systems	
	Status
All facility resource requirements are documented.	
Risk Element - 9 **Manufacturing Planning, Scheduling, and Control**	
Manufacturing Strategy and Planning	
Manufacturing strategy has been developed.	
Manufacturing plan under development and will be under continuous review.	
Manufacturing plan will be integrated with design plan and change control.	
Subcontractor / supplier management plan is in place.	
Critical schedule paths are identified.	
Manufacturing control hierarchy is in place.	

5 Assessment of Low Rate Initial Production

An important benefit of the MRL assessment for the HFCIT Market Transformation activity is the ability to establish jump-in and jump-out points for financial support of a particular market. To do this, the volume demanded by the market must be understood, as well as the volume that the manufacturer is capable of producing.

NREL interviewed PEM fuel cell manufacturers and reported the results in its report, 2007 Status of Manufacturing: Polymer Electrolyte Membrane (PEM) Fuel Cells.[13] Two of the manufacturing gaps for the assembly of PEM fuel cells highlighted in this report are:

- Gap #14 - The equipment for rapidly assembling cell stacks has not been developed and is a manufacturing gap. Currently, PEM cell stacks are assembled manually. Rapid assembly equipment does not exist. Aligning the MEAs, bipolar plates, and end plates is critical to preventing the buildup of stress on cells when the stack is placed under compressive load.
- Gap #15 - Manufacturers also need to develop quality control methods for rapid alignment of cell stack components. Correlations between cell alignment and cell stack durability need to be established.

NREL's interviews with PEM manufacturers established that the manufacturing gaps in the assembly of the cell stacks limits present production rates.

The Battelle market analyses[5,6] of PEM fuel cell systems identified emergency backup power and forklift trucks as market entry opportunities and estimated the volumes of fuel cells that would be demanded by these early market opportunities.

The FRPs based on the Battelle analysis are product and application specific. Table 3 identifies the market size for the two applications. Included in Table 3 is a subset of the forklift truck market for federal purchases by the Defense Logistics Agency (DLA) and the US Postal Service. The DLA forklift truck subset is an on-going procurement and demonstration.

At MRL – 7, LRIP is defined for the production of PEM fuel cell systems, and LRIP is product and application specific just as in the case of FRP. *NREL has defined LRIP as 1,000 units / year based on industry interviews and the most recent market information generated by Battelle.* The Battelle analysis for FAA tower emergency backup power assumes an instantaneous 75% penetration into the replacement market, which is high based on industry input. Industry anticipates the year one market entry to be several hundred units growing to 1,000 units per year over a two year period, i.e. growing to the LRIP value. The industry production numbers are consistent with present purchases.

For the forklift truck applications, Battelle identified the DLA and the US Postal Service as early adaptors of this technology with annual purchases of 472 units per year. The market penetration into the forklift truck replacement market was estimated to be 20% for all but the Class 2, narrow aisle, high reach forklifts, for which a 5% market penetration into the replacement market was estimated. LRIP at 1,000 units per year would deliver forklift truck PEM systems for the early adaptor market and support commercial market development. The LRIP of 1,000 units per year was confirmed during industry interviews with forklift PEM power systems manufacturers.

Table 3: Battelle market analyses data for Emergency Backup Power and Forklift Trucks

Market	Market Size	Annual Replacement Market	Replacement Market for PEM Fuel Cells in Initial Years
Emergency Backup Power	19,900	2,265	1,699
Forklift Trucks*	755,967	108,606	~5,000
DLA USPS Forklift Trucks	14,175	2,435	472

* 2006 estimate based on Scenario 3 of Battelle Report; see references 5 & 6

5.1 Emergency Backup Power

The Battelle market analysis for PEM emergency backup power applications rated reliability and start-up time as critical performance criteria for entry into the market. Lifetime of the emergency backup power unit, fuel availability, and ease of use were the next highest-rated criteria for entry into the market. Four of the five top criteria for purchasing emergency backup power units are associated with the technical readiness of the PEM fuel cell. A critical issue for emergency backup power is the requirement to continually maintain 911 response services. The FAA application also demands high reliability to insure emergency support for air traffic management. **For these reasons, the emergency backup power unit <u>needs to be</u> technically mature; at a TRL equal to 9.**

The Battelle analysis for emergency backup power for FAA applications predicts market volume at greater than 1,300 units per year. This market volume requires manufacturers to increase their production rate to near LRIP; 1,000 units per year.

The market size for the emergency backup power system places the manufacturing at LRIP conditions. **The MRL for emergency backup power <u>needs to be at least</u> MRL – 7.**

MRL-7: Prototype Manufacturing System.
Prototype system built on soft tooling, initial sigma levels established. System is ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling are proven. Materials initially demonstrated in production and manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Emergency backup power is a subset of a much larger backup power market opportunity that includes the commercial telecommunications market. The international commercial telecommunications market is growing at rapid pace, much faster than the federal market. Ballard Power Systems recently announced a binding agreement for ACME to purchase over 1,000 units in 2009 and 9,000 units in 2010.[18] **This single announcement by Ballard identifies an 8-fold increase in backup power applications compared to the FAA. By 2010 Ballard would need to increase the production rate from LRIP to FRP (> 5000 units / year for backup power).**

Auxiliary power PEM fuel cells can provide an alternative source of power operating over the very broad power range of 3 to 30 kW. Auxiliary power has many applications using carbonaceous fuel. PEM fuel cell auxiliary power units (APUs) provide an alternative source of power when the main engine, either an internal combustion engine or turbine, is not operating. The APU enables high efficiency cooling, lighting, and communications at remote sites. Fuel Cell Today's Niche Transport Study reports that the sales of fuel cell APUs for marine and leisure applications have doubled.[19] Fuel Cell Today additionally reports annual sales of APUs at 7,000 units for 2008. These sales figures consider two types of fuel cells; PEM fuel cells operating on hydrogen or reformed methanol and direct methanol fuel cells; the latter are not included in the MRA. **Estimating 30% penetration of the PEM fuel cells into the APU market establishes the base for APU manufacture at LRIP and the transition to FRP.**

5.2 Forklift Trucks

The Battelle market analysis of PEM-powered forklift trucks rated reliability, ease of use, and lifetime of the PEM fuel cells as all-important criteria for forklift trucks. Annual operating cost, fuel availability, and past experience (with PEM fuel cells) completed the higher rated criteria for forklift truck entry into the market. Start-up time, time between refueling, capital cost, and emissions in that order were the final criteria rated for market entry. Six of the ten criteria for purchasing the PEM powered forklift truck are associated with the technical readiness of the PEM fuel cell, with reliability identified as the highest rated criteria. **The PEM fuel cell forklift trucks <u>need to be</u> technically mature; at a TRL equal to 9.**

Three scenarios for forklift truck market entry are discussed in the Battle report[6] and these are:

1. There is no government subsidy or government action to promote PEM commercialization in the Base Line scenario.
2. The Communication scenario has the government conducting outreach programs to supply PEM fuel cell system information to the user. The government does not subsidize the purchase of the PEM systems in the Communication scenario.
3. The Subsidy scenario has a government subsidy of $1,000 per kW for the PEM fuel cell. This represents up to a 33% reduction in fuel cell cost that can be passed on to the commercial customer.

The results of the scenario analyses applied to Forklift Trucks are given in Table 4.

Table 4: Results based on Battelle PEM Market Analysis [6]			
Specialty Vehicles Fuel Cell Powered Forklift Trucks			
Market Segment	**Base Case**	**Communication Case**	**Subsidy Case**
Market Size	755,967	755,967	755,967
Market Penetration - %	40	40	40
Entry Market Size	<1,000	1,000	4,000
5 year Market size Annual Sales Units	4,085	6,009	26,830
Entry Price $/kW	3,000	3,000	3,000
5 year Price $/kW	3,000	3,000	3,000
5 Y ear Replacement Cost $	24,000	24,000	24,000
Today's Cost $/kW	>4,000	>4,000	>4,000
TRL at Market Entry	9 Final form	9 Final form	9 Final form
Needs to be at MRL at Market Entry	9 FRP	9 FRP	9 FRP

The Battelle analysis predicts a high manufacturing rate for the PEM-powered forklift trucks during the first five years. The production rate exceeds 1,000 units per year in the second year of production for the Base scenario. The Subsidy scenario exceeds production of 4,000 PEM powered forklift trucks in the first year. The scenario 3 market size for forklift trucks places the manufacturing at FRP conditions.

The market size for forklift trucks places the manufacturing at FRP conditions. **The MRL for the forklift trucks <u>needs to be at</u> MRL – 9.**

MRL-9: Full Rate Production demonstrated and lean production practices in place.

The system, component, or item is in full rate production. Technologies have matured to at least TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. System, components, or items are in full rate production and meet all engineering, performance, quality, and reliability requirements. All materials, manufacturing processes and procedures, and inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

The DLA has an on-going PEM forklift truck demonstration program with the purpose of increasing energy and operational efficiency at Defense Depots. The DLA is the second largest warehouse operation in the United States and successful implementation of the program could facilitate rapid growth of the PEM-powered forklift truck market as a commercial enterprise. The DLA is operating fuel cell powered forklift trucks at the Susquehanna, PA Defense Distribution Depot, and the DLA has initiated the program at the Defense Distribution Depots at Warner Robbins, GA, and San Joaquin, CA. The Battelle analysis[5] estimates the DLA would purchase 40 PEM-powered forklift trucks per year.

6 Manufacturing Readiness Assessment: Industry Status

The leading manufacturers of PEM fuel cells for forklift trucks, backup power, and/or APUs in North America are: Hydrogenics Corp., Nuvera Inc., Plug Power Inc., and Protonex, Inc. The first three companies manufacture PEM power systems for forklift trucks. Hydrogenics Corp, Plug Power Inc., and Protonex Inc. manufacture backup power and/or APUs. These four companies were contacted and asked to participate in an MRA. *One criterion for the MRA was that the individual MRLs would remain confidential and the data would be reported as agglomerate data with no specification of an individual companies' manufacturing readiness.* The company activities are briefly described in the following:

6.1 Hydrogenics, Corp.

Hydrogenics manufactures PEM fuel cell stacks and PEM fuel cell systems and view their operation as a "hydrogen engine" business. Hydrogenics "sells engines that go into end applications." Hydrogenics' has two main fuel cell products: Power packs for forklift trucks and power packs for backup power. Hydrogenics sees integrated systems, composed of on-site hydrogen generation, hydrogen storage, and fuel cells for electricity generation, as a growth area for the company.

6.1.1 Hydrogenics Forklift Trucks

Hydrogenics manufactures fuel cell power packs for forklift truck applications that generate up to 80 volts and 30 kW. The Hydrogenics power system is designed to replace batteries in electric forklift trucks and is not designed to replace internal combustion engines in forklift trucks. Hydrogenics delivers a complete battery replacement system that includes hydrogen storage, power electronics, and controls, all of which are designed to fit within the existing battery compartment of the forklift truck. Hydrogenics participates in the DLA's forklift truck demonstration at the Defense Distribution Depot at Warner Robins, GA. Hydrogenics' fuel cell-powered forklifts were demonstrated at General Motor's Canada assembly plant and by FedEx at Pearson International Airport in Toronto. Hydrogenics is working with the team of LiftOne and Engineered Solutions to develop a Linde fuel cell-powered lift truck.

6.1.2 Hydrogenics Backup Power

Hydrogenics' emergency backup power systems are based on a modular design that generates 4, 8, and 12 kW of power. Hydrogenics markets integrated backup power systems for communication systems. The Hydrogenics PEM power systems are also marketed to equipment manufacturers and system integrators for installation in emergency backup power systems. Hydrogenics sells their PEM systems to American Power Conversion (APC) for backup power applications. The APC cabinets can supply up to 30 kW of power, and cabinets can be ganged together to supply up to 300 kW. APC has installed backup power units containing Hydrogenics' fuel cell system at an internet service provider. Hydrogenics anticipates growth for their backup power systems and their business plan is to be a supplier to existing backup power manufacturers and deliver to them a high reliability fuel cell system.

6.2 Plug Power, Inc.

Plug Power (Plug) manufactures PEM fuel cell stacks and PEM fuel cell systems for forklift trucks, backup power, and on-site power generation. Plug builds their own stacks for these applications and has also established a PEM cell stack purchase agreement with Ballard Power Systems. The purchase agreement is a consequence of Plug's acquisition of Cellex Power Products and General Hydrogen Corporation. Both Cellex and General Hydrogen designed PEM fuel cell power systems for forklift trucks using Ballard Power System cell stacks. Plug provides fuel cell systems to three markets: backup power, motive power, and prime power. Motive power is the fastest growing market for Plug Power.

6.2.1 Plug Power Backup Power

For the backup power market, Plug sells the GenCore® system to the telecommunications market. The GenCore system uses hydrogen as a fuel and replaces valve regulated lead acid (VRLA) batteries as backup power for remote wireless networks. The GenCore provides extended life of up to 10 years while VRLA batteries tend to fail after three to five years. Plug Power's GenCore system is competing internationally and they are working with telecommunications consultants India Ltd. Market demand in India for extended backup power is very robust and the telecommunications market there is reported by Plug to be growing at 4 million subscribers per month.

6.2.2 Plug Power Forklift Trucks

For the motive market, Plug sells the GenDrive™ system for forklift truck applications and other industrial motive applications. The GenDrive system uses hydrogen as the fuel and delivers increased efficiency to warehouse operations by eliminating long recharging times and improving high power operation throughout the entire shift. The system is designed to fit seamlessly into the existing battery compartment. The GenDrive systems are available for pallet trucks and sit-down rider trucks. General Hydrogen, a wholly-owned subsidiary of Plug Power Inc. has the task of retrofitting 20 battery-powered Class 1 forklifts at the Defense Distribution Depot in Susquehanna, PA with General Hydrogen's fuel cell power packs. Cellex Power Products operated forklifts at Wal-Mart facilities and brings this demonstration experience to Plug Power. In late 2008, Plug Power sold over 200 fuel cell units for installation in Yale Equipment Services forklifts.

6.3 Nuvera Fuel Cells

Nuvera manufactures PEM fuel cell stacks and PEM fuel cell systems including fuel-processing products. The important markets that Nuvera's PEM fuel cell and fuel-processing systems address are industrial vehicles and equipment, power generation, and the transportation industries.

6.3.1 Nuvera Forklift Trucks

Nuvera has developed a stand-alone motive power source, PowerFlow™, for use with forklift trucks and industrial vehicles. The PowerFlow system can be integrated with a battery to provide hybrid power for industrial vehicles. The 5-kW power system uses Nuvera's metal plate open flow field technology to facilitate high power density operation. Nuvera reports 10,000-hour durability for their cell stack.

6.4 Protonex Technology Corporation

Protonex Technology Corporation (Protonex) manufactures PEM fuel cell stacks and PEM fuel cell systems at the 10 watt to 1,000 watt rating. They develop hybrid power systems and fuel cell systems and batteries. The PEM fuel cells operate on reformed methanol or hydrogen from chemical hydrides. Protonex has developed an adhesive-bonded stack that has the seal injection molded into the assembled stack. The adhesion-bonded stack provides for a very simple assembly procedure and reduced manufacturing steps.

6.4.1 Protonex Auxiliary Power Unit

Protonex has developed a methanol-fueled hybrid 250-watt auxiliary power unit (APU) for the recreational vehicle market. Protonex believes that the appeal of low noise, vibration, and emissions will make hybridized fuel cells an attractive option for this market. Protonex stated the cable television market provides an important backup power opportunity with a base on the order of one million units. Their business strategy is to address multiple applications with the same (or very similar) power systems.

6.4.2 Protonex Backup Power

Protonex' power system is smaller and lighter than the VRLA battery bank used for backup power and emergency power. The power unit provides 250 watts of reliable power for operating small emergency systems or for recharging battery systems.

7 Manufacturing Readiness Assessment: System Manufacturing

The Manufacturing Readiness Worksheets, identified in Table 2 and Appendix B, were analyzed by NREL with respect to PEM fuel cell stack manufacturing and PEM fuel cell system manufacturing. Where possible, the worksheet questions were merged to optimize the assessment process and to specifically address the status of manufacturing PEM fuel cell stacks and systems. These relevant questions were collected and organized in a questionnaire for self-assessment by the four PEM fuel cell companies; Hydrogenics, Plug Power, Nuvera, and Protonex. The PEM questionnaire was used by NREL and industry representatives to assess the manufacturing readiness of the four companies interviewed. The PEM questionnaire is given in Appendix C.

The MRAs of the PEM fuel cell companies addressed three PEM manufacturing categories: (1) forklift truck fuel cell systems; (2) backup power/APU fuel cell systems; and (3) a combined category of forklift truck and backup power/APU fuel cell stacks. Information for systems and stacks is given separately for a number of reasons. Stack manufacturing capabilities are often more advanced and/or stack designs are more defined than PEM systems because applications for the systems are in many cases still being validated.

7.1 Fuel Cell Systems for Forklift Trucks

Hydrogenics, Nuvera, and Plug Power manufacture and assemble PEM fuel cell systems for forklift trucks. All three organizations have established demonstration programs in cooperation with forklift truck manufacturers, commercial interests (e.g. Wal-Mart), or with the DLA. The three fuel cell manufacturers plan to manufacture fuel cells for the three categories of forklift trucks:

- Class 1. Forklifts are electric-motor rider trucks, either stand-up operator or seat operator.
- Class 2. Forklifts are electric-motor trucks for narrow aisle or inventory stock/order picking applications, and include extra reach capability.
- Class 3. Forklifts are electric-motor trucks, either walk-behind or standing-rider operated.

7.1.1 Industry Self-assessment and Consensus MRLs

The aggregate self-assessment and consensus MRLs are reported in Table 5. The PEM power system manufacturing data for the three classes of forklift trucks are aggregated to maintain confidentiality since not all of the PEM manufacturers reported results as a function of the forklift class. The range of the risk element assessments using the PEM MRA questionnaire in Appendix C varied among the three companies, as shown graphically in Figure 4.

Table 5 : Manufacturing Readiness Assessment PEM Power Systems for Forklift Trucks		
MRLs Forklift Trucks	**Companies' Self-assessment**	
Risk Element	**High**	**Low**
Technical Maturity	8	7
Design	8	5
Materials	8	6
Cost & Funding	7	4
Process Capability & Controls	7	5
Quality	8	5
Personnel	8	6
Facilities	8	6
Manufacturing Planning, Scheduling, Control	7	7

The graphic representation in Figure 4 portrays the MRL band of MRL-4 to MRL-8 for the risk elements of the aggregate company data. The MRL - 4 rating of the risk element Cost & Funding reflects the start-up characteristics of the forklift truck commercialization effort. Stack components and balance-of-plant components are making the transition from laboratory prototype development and acquisition to full scale production, acquisition, and assembly. For those companies who have reached MRL – 7 for the Design risk element, there is a higher level of comfort in the Cost & Funding risk element. Where there are significant changes reported for the Design risk element (MRL – 5), the risk elements Cost & Funding, Process Capabilities & Controls, and Quality also reveal greater uncertainty in attaining the LRIP operating condition.

The manufacturing readiness based on the aggregate data indicates that the PEM power system industry for forklift trucks has a broad range of risk element rankings. The lowest ranked risk element is Cost & Funding, which covers a span of three MRLs: MRL – 4 to MRL – 7.

The high end rankings for risk elements Design, Process Capability & Control, and Quality have achieved MRL – 7 or MRL – 8, while the low end ranking is MRL -5. Manufacturing research and development on Process Capability & Control and on Quality can increase the manufacturing rankings to the LRIP stage. The MRL – 5 ranking of the Design risk element identifies an unstable design element that is sufficiently serious to delay progress in other low risk elements.

Materials, Personnel, and Facilities span a much narrower risk element ranking range; MRL – 6 to MRL -8. The risk element Materials requires inventory control, material storage, and environmental issues be addressed in the manufacture of PEM power systems for forklift trucks. The Personnel risk element requires the development of training programs for specialty manufacturing skills to be put in place. The Personnel training would need to include training in process control and quality management. The Facilities risk element awaits physical changes in layout of the manufacturing processes to optimize the LRIP processes. These Facility risk elements can include setup of the workstations, construction of inventory facilities, and the installation of capital equipment.

The industry self-assessment data yielding high rankings; i.e. MRL – 7 and MRL – 8, substantiate the LRIP operating condition for five of the risk elements. The low rankings identify areas of manufacturing development that need resolution prior to fully achieving LRIP.

While the self-assessment variation company-to-company is real, NREL observed that some companies were very optimistic in their self-assessment while other companies were very conservative. An important criterion is a company's ability to deliver PEM power systems for installation into forklift trucks.

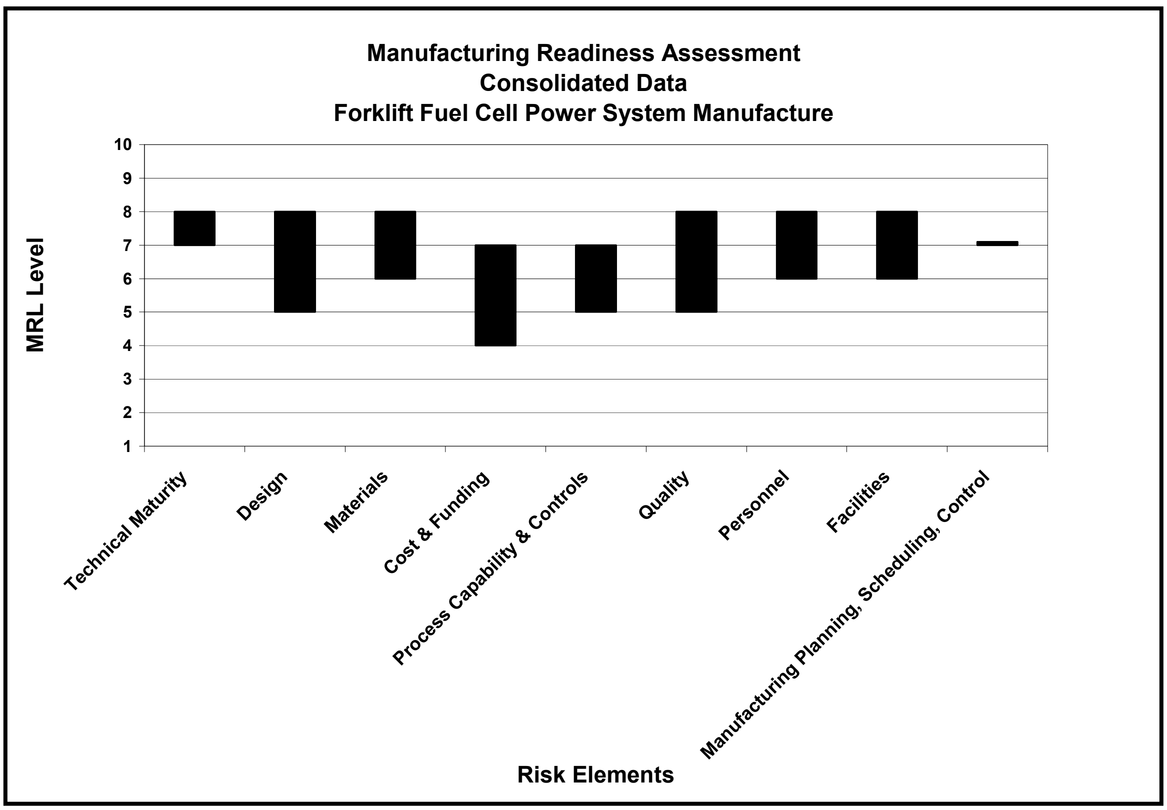

Figure 4: Industry self-assessment and consensus MRLs for forklift truck systems

7.1.2 NREL Assessment

All three companies have established workstation assembly of the forklift PEM power systems and have organized their production facilities based on the well established Lean Manufacturing principles.[20] None of the production processes for system manufacturing were automated at this early stage of production. The approach and manufacturing philosophy discussed by all three manufactures included the "Just In Time" (JIT) concept to minimize inventory. Implementation of the JIT concept is complicated by the limited demand for the PEM forklift power systems. In some cases, the workstations did not have production personnel. NREL concluded that the MRA was conducted during a transition stage for all of the manufacturers where the manufacturing processes are being expanded in anticipation of increased market demand. Not all of the companies have completed their facilities upgrades to meet targeted production. Those companies that had not increased the number of workstations in their facilities to achieve targeted production had facility expansion programs underway and were confident they would be production ready to fulfill market demand.

All three companies have experienced manufacturing management that are aware of the need for manufacturing efficiency and cost reduction. The companies are organizing their production capabilities to promote an orderly work flow environment with rapid assembly of the fuel cell power systems. Using existing workstation facilities, the companies have conducted time studies to accurately measure their production capability. One company reported execution of a "Run at Rate" experiment confirming capability to produce 1,000 power systems per year; while another company reported their time studies projected to 1,250 power systems per year. **Based on the reported company time study assessments, the companies are confident their current manufacturing capabilities can achieve LRIP of 1,000 forklift power systems per year.**

A caveat to the companies' LRIP assertions is the lack of personnel at all of the companies to implement manufacturing at 1,000 power systems per year. An important risk element of manufacturing readiness is Personnel Training and a MRL of 7 requires *all training programs in place and operational*. It is the *operational* requirement of the Personnel risk element that is holding companies back from achieving MRL-7.

An important reason that no company is operating at LRIP of a 1,000 units per year is the industry is in the demonstration stage and proving the value of PEM-powered forklift trucks to the customer. NREL anticipates the transition to LRIP for forklift truck PEM power systems will take 12 months for most if not all of the companies.

7.2 Backup Power and APU Fuel Cell Systems

PEM fuel cell systems for emergency backup power and APUs are considered in the same category because of their similar requirements: unattended operation for up to 24 – 72 hours, a PEM power system that is part of a hybrid battery system, power systems that are easily refueled, and a minimum five year life. Hydrogenics, Plug Power, and Protonex have established demonstration programs with prospective customers. There is a large difference in the ratings of these power systems with the Protonex APU at a maximum rating of 1 kW while the emergency backup power systems are rated 2 kW to 5 kW.

7.2.1 Industry Self-assessment and Consensus MRLs

The aggregate self-assessment and consensus MRLs are reported in Table 6. The range of the risk element assessments using the NREL-developed PEM questionnaire in Appendix C varied among the three companies as shown graphically in Figure 4.

The manufacturing readiness of the PEM emergency backup power & APU industries has not achieved LRIP. The lowest rated risk element is <u>Personnel,</u> which includes preparation of training programs for manufacturing, preparation of the trainers, instruction, and skill development of manufacturing personnel, and verification of the skill during pilot line production. The ranking range for <u>Personnel</u> is MRL – 4 to MRL – 6. The MRL - 4 rating of the risk element <u>Personnel</u> reflects the emphasis of the industry on development and demonstration of a prototype design. The transition from laboratory prototype to pilot line production will require personnel training.

The <u>Design</u> risk element is rated at LRIP (MRL-8) or "Ready for LRIP" (MRL-7) signifying there are either no design changes or the design changes have decreased and are minimal. With a validation of the design of emergency backup power and APUs, the market demand becomes the driving force for increasing manufacturing readiness.

Table 6: Manufacturing Readiness Assessment - PEM Power Systems for Emergency Backup Power and APUs

MRLs APU & Backup Power	**Companies' Self-assessment**	
Risk Element	**High**	**Low**
Technical Maturity	8	7
Design	8	7
Materials	8	7
Cost & Funding	6	5
Process Capability & Controls	6	5
Quality	7	6
Personnel	6	4
Facilities	8	8
Manufacturing Planning, Scheduling, Control	7	6

The risk element <u>Process Capability & Controls</u> ranking has a very narrow range: MRL – 5 to MRL – 6, and while the span of this risk element is narrow it is below the LRIP rating. The MRL – 5 rating of this risk element reveals the strong emphasis on developing and demonstrating a prototype that will stimulate market demand. The high end rankings for this risk element show that manufacturing processes have not been fully proven for the pilot line production and major changes to the production scale processes may be necessary. Increasing the ranking of this risk element for emergency backup power & APUs will require manufacturing development and establishment of greater process control.

The MRL – 5 ranking for risk element Cost & Funding is a sign of the emphasis on the prototype development and demonstration of this technology. The Cost & Funding risk element has a narrow ranking range of one MRL. Manufacturing activities addressing process and tooling needs are limited and investment requirements for the manufacturing process are only starting to be considered. Some companies reported cost reduction plans were being started and that Make / Buy programs were in the early stages. Considerations of cost controls for suppliers are still in the early stages. Manufacturing R&D will improve the Cost & Funding risk element ranking and elevate it to "ready for LRIP."

The two risk elements Quality and Manufacturing Planning, Scheduling, & Control are ranked in the range of MRL -6 to MRL – 7; the latter being "ready for LRIP." At the MRL – 6 stage, the quality and reliability specifications for the production process are being set. The work with subcontractors is addressing quality and reliability of the components when they are produced at LRIP rates and at costs consistent with LRIP requirements. Manufacturing planning is in the final data collection stage and critical schedule pathways are being identified for LRIP rates.

The four risk elements Technical Maturity, Design, Materials, and Facilities are all "ready for LRIP" at MRL – 7 or have advanced to LRIP at MRL – 8. The focus of the manufacturing development efforts is to increase the ranking of risk elements lower than MRL -7. Planning and activities for Full Rate Production, MRL – 9, were not reported by the emergency backup power & APU companies. The risk element ranking is graphically presented in Figure 5.

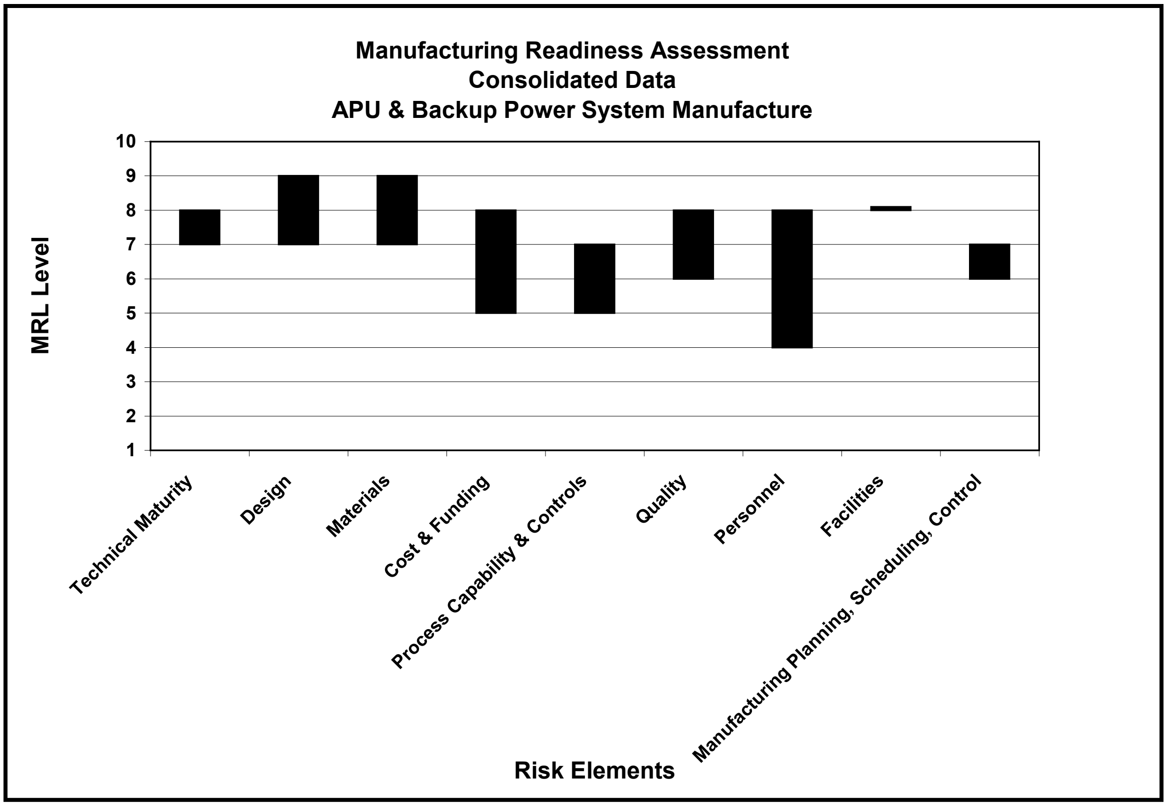

Figure 5: MRA industry self-assessment PEM power systems for emergency backup power & APUs

7.2.2 NREL Assessment

The manufacturing structure for all three companies is based on Lean Manufacturing, but the implementation of the Lean Manufacturing principles is hindered by the limited market demand. Personnel are not dedicated to specific workstations and move between workstations. Demand for 1,000 power plants per year has not developed, although all three companies forecast increased demand and have designed the manufacturing processes accordingly. Some of the companies have installed all of the workstations to produce at 1,000 power plants per year while others are planning to increase the number of workstations to meet market demand. Company manufacturing growth is driven by the market demand.

Using existing workstation facilities, the companies have conducted time studies to measure their production capability and efficiency. The time studies were used to design and optimize an orderly work flow at the workstations, and the companies concluded production rates of 200 to 300 units per year were readily achieved. **Increasing the number of workstations and personnel would result in LRIP of emergency power systems & APUs.**

8 Manufacturing Readiness Assessment: Stack Manufacturing

Hydrogenics, Nuvera, Plug Power, and Protonex manufacture cell stacks for their PEM fuel cell applications. In addition, Plug Power purchases PEM cell stacks from Ballard Power Systems. The manufacturing processes used to construct the cell stacks are characteristic of the varied designs of these companies' PEM technology. In particular, the Protonex adhesion bonding method of building stacks[21] is very different from the more traditional method of cell stack assembly.

The cell stack manufacturing maturity for all four companies is guided by the market demand for the emerging PEM fuel cell applications. The companies have established workstations for the manufacture and assembly of the cell stacks and the organization of the workstations is based on Lean Manufacturing principles. None of the stack assembly workstations use automated methods. The manufacturers attempt to control inventory by operating with the "Just In Time" approach for component and stack assembly. This approach is complicated by the large number of components required to assemble the cell stack and the present fluctuating market demand. The number of stack assembly workstations is limited at all of the companies; however, the existing workstations have demonstrated acceptable production rates. **All of the companies reported that increasing the number of workstations and / or the personnel will achieve LRIP of 1,000 cell stacks per year.**

8.1 Industry Self-assessment and Consensus MRLs for Cell stack Production

The aggregate self-assessment by the companies is given in Table 7. The range of the risk element values using the NREL-developed PEM questionnaire in Appendix C varied among the three companies; significant variation exist for the two risk elements Cost & Funding and Personnel. The companies' self-assessments for the risk elements are shown graphically in Figure 6.

Table 7: Manufacturing Readiness Assessment PEM Cell Stacks		
MRLs Stacks	**Companies' Self-assessment**	
Risk Element	**High**	**Low**
Technical Maturity	8	7
Design	9	8
Materials	9	8
Cost & Funding	8	5
Process Capability & Controls	7	7
Quality	8	6
Personnel	8	4
Facilities	8	8
Manufacturing Planning, Scheduling, Control	8	7

The high ranking column of the risk elements in Table 7 identifies PEM cell stack manufacturing at "ready for LRIP" at a minimum and in some case preparing for the transition to FRP.

The risk element Cost & Funding covers the range MRL – 5 to MRL – 8. The companies with the lower rating emphasized the development and demonstration of the prototype design and are only beginning to implement cost reduction programs. Some of the risk element criteria have been met; e.g. Make / Buy programs have been initiated, while other risk elements such as cost controls on the suppliers and subcontractors have not been achieved. The poor cost control on the suppliers may be resolved as increasing production volumes provide leverage for supplier cost control.

The risk element Quality covers the range MRL – 6 to MRL - 8 and shows that final quality and reliability levels for some stack manufactures have not been established. In addition, quality and reliability requirements have not been set for the suppliers and subcontractors. The risk element Quality can be easily elevated to MRL – 7 ("ready for LRIP") because the ranking of the two risk elements Design and Materials are both mature (at MRL – 8, "operating at LRIP") permitting development efforts to focus on quality.

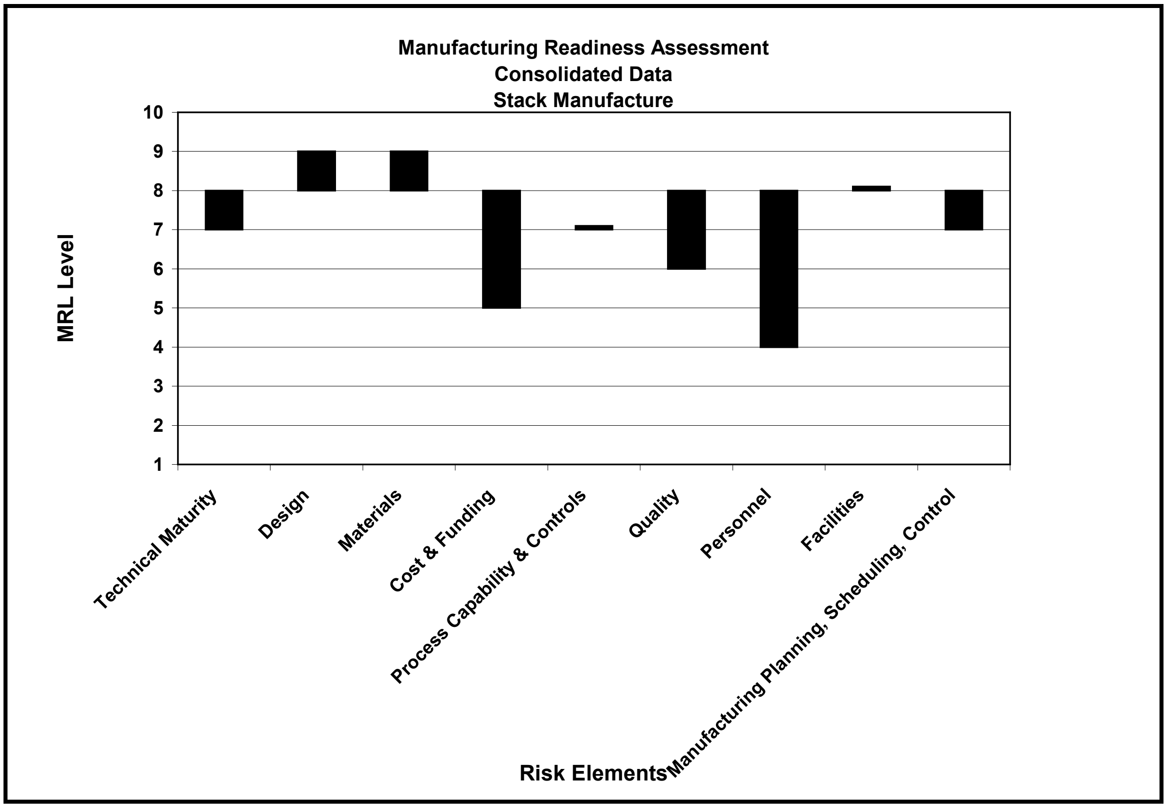

Figure 6: MRA industry self-assessment PEM cell stack manufacturing

8.2 NREL Assessment

Three risk element outliers for cell stack manufacturing need to be addressed by the companies: Personnel, Cost & Funding, and Quality. The assessments of the risk element Personnel cover the broad range from "At LRIP and all specialty training skills are verified" (MRL – 8) to "Training programs are being identified" (MRL – 4). The greatest problems expressed by some of the companies for risk element Personnel were the development and implementation of training programs and the staffing requirements.

Some companies have not fully implemented cost control measures and this is reflected in the high cost range for emergency backup power; \$6,000/kW to \$3,000/kW.[5] The validation programs operated by the government agencies accept these high costs; however the market transformation to commercial systems is a driver for companies to compete and reduce costs.

9 Key Barriers to Achieving Low Rate Initial Production

In addition to completing the NREL-developed PEM questionnaire with the manufacturers, as described above, a general discussion was held with each manufacturer to obtain their input on future activities that DOE could support with the objective of assisting industry in reaching, and later surpassing, LRIP. As would be expected, varied responses were received from the manufacturers given the different manufacturing processes and competencies of each company. However, some clear similarities emerged.

- Testing and quality control was an issue mentioned by all four manufacturers. Quality control in the assembly of stacks is slowing the development of cell stack assembly using automation. In-line quality control measurements and methods of positioning cell components with reliability, accuracy, and at high rates are common needs for all manufacturers. The development of semi-automated and fully-automated stack and system assembly techniques is a critical benefit for cost reduction at LRIP and a critical requirement for FRP.
- The long time periods required for stack and final system conditioning and testing were repeatedly identified as a major barrier to rapid assembly of systems. Stack and system conditioning are time consuming and costly. Manufacturers recommended developing a suite of short term tests that would correlate with durability and reliability of the stack and system.
- Balance of plant (BOP) subcomponent testing was also identified as a barrier. A better understanding of the quality variability of BOP components was clearly identified as an industry need.
- Support for design-for-manufacturability analyses was suggested. One manufacturer commented that transition to full rate production will require a total redesign of manufacturing capability and facilities, and may even require a redesign of the stack or system itself.

10 Conclusions: Manufacturing Readiness Assessment PEM Stacks and Systems

NREL developed a MRA process for evaluating PEM system and stack manufacturing status that builds on evaluating nine risk elements: Technical Maturity, Design, Materials, Cost & Funding, Process Capability & Controls, Quality, Personnel, Facilities, and Manufacturing Planning, Scheduling & Control. When applying the MRA to several companies, a broad range of rankings within a risk element can occur that highlight the diverse production capabilities of these companies.

NREL assisted in manufacturing readiness self-assessments by PEM fuel cell stack and system manufacturers for forklift trucks, emergency backup power, and APU applications. NREL developed a questionnaire to facilitate the MRAs by the companies, collected the data, and produced an aggregate database identifying the collective status of the manufacturing capability of the PEM system and stack manufacturers. The database maintains anonymity for the companies while ranking the manufacturing capability.

All of the companies are making the transition from research, development, and demonstration-guided activities to market-guided activities with a strong emphasis on establishing a manufacturing process for a fixed PEM design. This beginning stage of market transformation has changed the investment strategies of the companies to emphasize reproducible production of a PEM system / stack with high levels of quality control of the PEM design and the manufacturing process. The emphasis on meeting market demand imposes cost limitations on the PEM technology and the companies are addressing cost-driven design, performance, and delivery requirements.

The NREL-developed MRA brought into focus the manufacturing risks associated with achieving LRIP of 1,000 PEM systems per year. Four important conclusions are the result of the companies' self-assessments and NREL's assessment of the manufacturing status.

1. Based on the reported company time-study assessments, PEM companies are confident their manufacturing approaches can achieve a LRIP of 1,000 forklift truck PEM power systems per year. The companies are not at the 1,000 unit LRIP today for forklift PEM power systems. Based on current market demand, actual production rates are currently in the range of 200-300 units per year.
2. Based on the reported company time-study assessments, PEM companies are confident their manufacturing approaches can achieve a LRIP of 1,000 power systems per year for emergency backup power & APUs. The companies are not at the 1,000 unit LRIP today. Based on current market demand, actual production rates are currently in the range of 200-300 units per year.
3. The Manufacturing Readiness for cell stacks is the most advanced of the three manufacturing capabilities assessed. There was a high level of risk for stack development for staffing and training of production personnel. Importantly, costs of the cell stack also represent a risk. Because the cell stack is an integral and dominating component of PEM systems, resolution of these two risk issues, Personnel and Cost, are critical for companies to achieve market transformation into a FRP.
4. The risk elements Cost & Funding, Personnel, and Quality had lower rankings for forklift truck and emergency backup power & APU applications. NREL considers these low ranking risk elements to be representative of the transition from PEM prototype development to a stable, commercial PEM system design. The establishment of a stable PEM design changes the emphasis from demonstration to high rate quality production of a cost competitive PEM system by trained personnel.

While the system and stack MRAs demonstrated large MRL ranges within many of the risk elements, it is instructional to consider both the minimum and the maximum aggregate MRLs. The minimum MRLs indicate the critical risk areas that must be addressed to reach a manufacturing maturity that will support LRIP across the entire manufacturing enterprise. The reasons for and implications of the low MRLs have been discussed in sections 7 and 8. However, an assessment of the maximum aggregate MRLs gives a different perspective. As can be seen in Tables 5-7, the maximum MRLs in almost all cases describe a near-readiness for LRIP. In other words, in aggregate, the industry already possesses the technologies and best practices needed for production at LRIP – what is needed are the market conditions to enable each manufacturer to address their specific risk areas.

11 Recommendations

11.1 Recommendations based on the manufacturing readiness assessments

Two risk elements with poor rankings identified by the MRAs of the three applications (forklift trucks, emergency backup power and APUs), are Cost & Funding and Personnel. The major barrier for both of these risk elements is market demand. The fuel cell manufacturers have emphasized research, development, and demonstration to establish applications. Even with these efforts, the market pull has not developed.

- Increasing the market demand will provide the impetus for fuel cell manufacturers to increase production staff, implement training programs, and resolve and improve the ranking of the Personnel risk element. **Market transformation programs that identify mission structure applications for fuel cells are designed to increase market demand and are recommended.**
- The present platinum content combined with the cost of platinum catalyst causes a high initial purchase price for PEM fuel cells. **R&D support to lower the catalyst content and drive down the initial purchase price of fuel cells is recommended.**

The risk element Quality is the third common problem area identified by the MRAs. All cell stacks and fuel cell systems currently require conditioning and continuous operation prior to delivery to the customer. The conditioning process is costly, time consuming, and requires expensive testing equipment. In-line, continuous quality control measurements are rare and not fully developed for the assembly of cell stacks and fuel cell systems. In stack manufacture, in-line quality control methods for the inspection of cell components do not exist. With the transition to FRP, the requirements for in-line, high rate quality control methodology will increase. **Quality control methodologies for stack component inspection and reduction of cell stack and fuel cell system conditioning time are a recommended area for DOE support.**

11.2 Programmatic Recommendations

The MRA provides an assessment of the progress of a manufacturer toward LRIP and FRP for a given market segment, using a standard methodology that can lead to comparative and agglomerate analyses of the industry. The evaluation of LRIP for an emerging market and the assessment of a manufacturer's ability to produce at LRIP can be used as "jump-in"/ "jump-out" criteria for market transformation decision makers. In addition, information for reporting of progress toward HFCIT goals and for identifying new areas for manufacturing R&D is generated. **An ongoing MRL assessment activity should be established in support of the HFCIT Market Transformation activity. Participation in this activity should be a requirement for all co-funded demonstration activities so that unbiased, comparative assessments can be made.**

The MRA conducted with the assistance of Hydrogenics, Nuvera, Protonex, and Plug Power assessed the manufacturing status of fuel cell power systems for forklift trucks, emergency backup power and APUs, and cell stack manufacture. Plug Power uses its fuel cell stack and the Ballard Power Systems fuel cell stack. Discussions are underway for Ballard to participate in a self-assessment of fuel cell stack manufacturing. The self-assessment will probably occur within the next six months. **The MRA of Ballard cell**

stacks is an important metric of fuel cell stack manufacturing, and should be included as a follow-on activity to this report if possible.

While the MRA reported here addressed cell stacks, the MRA did not rank the manufacturing status of cell stack component manufacture. Manufacture of bipolar plates and membrane-electrode-assembly (MEA) components are critical, time consuming, and costly processes for the manufacture and commercialization of fuel cells. A 5-kW stack will contain 20 to 25 MEAs per stack and an equal number of bipolar plates. Manufacturing rates for the MEAs and bipolar plates need to be up to 25 times greater than stack manufacturing rates. Over 90% of the MEA cost is materials, thus process control to reduce scrap and rework is critical. Quality is an important risk element for cell components. Each of the 25 MEAs has four edges to be sealed and each of the bipolar plates has four edges to be sealed to the MEAs; operation at less than six sigma (3.4 failures per million) will increase rework and overall costs. **The manufacturing readiness of the cell components is critical to the commercialization of PEM fuel cells and should be assessed as a follow-on activity of this report.**

Assessing automotive cell component and stack manufacture introduces a new level of quality and cost control. The quality issue stems from the large number of cells per automotive stack – 180 to 230 cells per stack with two stacks per power system – and the large number of stacks to be manufactured. LRIP for the automobile industry is in the range of one million cell stacks per year based on 500,000 vehicles (less than 4% of the North American market). Over 200 million MEAs would need to be manufactured annually or 400 MEAs per minute. Process control of multiple manufacturing facilities will be critical to achieving MEA compatibility for automotive applications. **The MRA of automotive cell component and cell stack manufacturing is critical to forecasting the entry of PEM fuel cell powered vehicles.**

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Air Force Transition Readiness Level Calculator, Version 2.2

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Appendix A
Manufacturing Readiness Levels Final Report
HFCIT Technology Readiness Levels

The National Renewable Energy Laboratory developed TRLs incorporating inputs from the Department of Energy for the HFCIT Program fuel cell activities and from the hydrogen storage activities

TRL 1 Basic research with basic principles observed and reported:

- The essential characteristics and behaviors of systems and architectures have been defined.
- Scientific research begins to be translated into applied research and development.
- Fundamental understanding of physical phenomena is developed. Potential may exist for multiple applications, with no specific application emphasized

TRL 2 Applied research and technology concept is formulated and invention process begins:

- Applied research is undertaken with the transition from TRL 1.
- Theory and scientific principles define the concept for specific application.
- Characteristics of the application have been described. Analytical tools have been developed for simulation or analysis of the application.
- Invention begins based on practical application of basic principles.
- Fundamental understanding is utilized to assess concept viability for the targeted application and need for further R&D is identified
- Exploratory concepts and approaches are developed and targeted for a specific application.

TRL 3 Concept validation and characteristic proof-of-concept demonstration

- Concept validation has been achieved with demonstration of technical feasibility using breadboard or brass-board implementations.
- Applied research and development continues. Initial laboratory measurements studies validate analytical predictions of separate elements of the technology.
- Technology is incorporated into a first generation component/process design. Component/process design activities may be assisted by performing:
  - Analytical studies
  - Laboratory experiments
  - Modeling and simulation
- New technical barriers associated with moving the technology from lab data to component/process development are defined

TRL 4 Component/subsystem validation in laboratory environment:

- Prototyping implementation and testing have been demonstrated.
- Integration of technology elements has been demonstrated.
- Design, development and lab testing of technological components provide evidence that applicable component/process performance targets may be attainable based on projected or modeled systems.
  - Technology demonstrates functionality of component/process in simplified environment

    - Draft component/process conceptual design has been documented
    - Performance metrics for component/process have been established and documented.
    - Cross-technology issues (e.g., H2 quality) have been identified.

TRL 5 System/subsystem/component validation in relevant environment:

- Thorough testing of prototyping in a representative environment validated in the laboratory.
- Major components integrated in breadboard evaluation.
- Technological components/process steps are integrated with supporting elements so that the technology can be tested and verified in the lab.
    - System engineering and analysis studies address cost, performance, integration, and interfaces, are completed
    - A semi-integrated to fully integrated system assembled in the laboratory that simulates full scale integrated.
    - The semi/fully integrated system/process tests results verify that when projected to full scale operations, the system/process can meet the targets for commercialization

TRL 6 System/subsystem model or prototyping demonstration in a environment:

- Representative model or prototype system has been tested in a relevant environment.
- Fully integrated system built, tested and verified. Results demonstrate that the system/process will meet all targets at full scale.
    - Materials, process, design, and integration methods have been defined.
    - Scaling issues that remain are identified and supporting analysis is complete.
    - System integration issues have been identified and major issues have been addressed.
    - Results meet the system/process targets for commercialization.
    - The system/process specifications are complete
    - Scaling issues are identified and supporting analysis is complete.
    - Production issues identified and resolved.
    - Actual reliability, availability and maintainability data obtained from the prototype, analyzed, and issues resolved

TRL 7 System prototyping demonstration in an operational environment:

- System prototype demonstrated in an operational environment.
- Integrated test vehicle with collateral and ancillary systems completed.
- Technology verified at semi-commercial/commercial scale. System completed and qualified through test and demonstration.
    - Materials, process, design, and integration methods are complete.
    - System integration issues identified and addressed.
    - System/process is tested for extended periods of time.
    - System/process specifications are complete.
    - Production issues identified and resolved.

    - Collection of actual system reliability, availability and maintainability data obtained and issues resolved.

TRL 8 System completed and incorporated in commercial design and proven through testing in an operational environment:

- End of system development.
- Fully integrated operational hardware and software systems developed.
- Technology proven to work in final form under real-world conditions.
- System incorporated into commercial design.
    - Technology successfully completed operational demonstration and evaluation.
    - Safety/Adverse effects issues identified and mitigated technology is available from one or more vendors for commercial sales

TRL 9 System is successfully demonstrated in field:

- Fully integrated operational hardware/software systems have been developed.
- Actual application of the technology is in final form and demonstrated in the field.
- All documentation has been completed.
- Sustained engineering support is in place.

Appendix B
Manufacturing Readiness Assessment
MRL-5 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 5 Worksheet[1]	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.

Application PEM Stacks and PEM Systems	
	Status
Risk Element 1 Technology and Industrial Base	
Technical Maturity	
Program has achieved TRL-5	
Plans to reduce manufacturing technology barriers have been implemented	
Targets for improved yield established	
Pre-production process equipment available	
Prototype materials, prototype components, tooling and test equipment in development for pilot line production.	
Trade studies and laboratory experiments under way to define critical manufacturing processes.	
Manufacturing process still in development	
Industrial subcontractors and production capacity	
Subcontractors are identified.	
Contingency requirements have been evaluated and documented	
Long-lead issues under study.	
Plans prepared and accepted to mitigate schedule delays	

Appendix B
Manufacturing Readiness Assessment
MRL-5 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 5 Worksheet[1]	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.

Application PEM Stacks and PEM Systems	
	Status
Risk Element 2 **Design**	
Does the engineering plan support manufacturing of evolving design?	
Integrated Product Team has established design and manufacturing approach	
Engineering change process includes production / manufacturing and quality representation.	
Configuration management process is tracking subcontractors	
There are no significant design and engineering changes	
Component testing completed for "changed" processes.	
Design for Manufacturing	
Performance trade studies for alternative designs are complete.	
Producibility engineering trade studies are complete.	
Component and hardware requirements established.	
Does manufacturing plan evaluate the producibility of system and components?	
System design with changes is still a low risk for manufacturing	
"Design to Cost" criteria are maintained	
Tooling design plan	
Special tooling and test equipment under test.	

Appendix B
Manufacturing Readiness Assessment
MRL-5 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 5 Worksheet[1]	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.

Application PEM Stacks and PEM Systems	
	Status
Risk Element 3 **Materials**	
Material Standardization	
Material standardization plan developed	
Material Availability & Handling	
Material control and inventory control processes are in place	
Environmental issues with materials are addressed or a plan is in place to address environmental issues	
Risk Element 4 **Cost and Funding**	
Design to Cost	
Manufacturing costs are estimated and being reviewed and revised.	
Program making progress to identifying component cost goals.	
Investment needs for process and tooling determined	
Make / Buy program is initiated	
Cost Drivers	
Has a cost center been established?	
Progress toward costs traceable to manufacturing process steps being made.	
Analysis of non-recurring capital and engineering costs ongoing	
Subcontractors and suppliers cost control identified	

Manufacturing Readiness Level 5 Worksheet[1]	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.

Application PEM Stacks and PEM Systems	
	Status
Risk Element 4 **Cost and Funding continued**	
Cost Reduction Plan	
Cost reduction plan is operational and contributing to reducing cost.	
Cost model is developed.	
Risk Element 5 **Process Capability and Control**	
Manufacturing Processes	
Key manufacturing processes assessed for pilot line.	
Processes requiring major production-scale related changes identified	
Initial assessment of assembly needs performed	
Progress is made on pilot line build.	
Manufacturing Process Control	
Analysis of production throughput initiated.	
Yield issues have been defined and rationalized	
Risk Element 6 **Quality**	
Quality Strategy	
Continuous process improvement program in place and working.	
Metrology program in place.	

Manufacturing Readiness Level 5 Worksheet[1]	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.

Application PEM Stacks and PEM Systems	
	Status
Quality and reliability requirements under development.	
Progress toward analysis of system Sigma levels.	
Supply Chain Quality	
Quality and reliability requirements have been flowed down to subcontractors	
Risk Element 7 **Personnel**	
Specialty Skills & Training	
Personnel skills have been demonstrated on components in laboratory.	
Training program necessary for specialty skills initiated.	
Training programs in place for Process Control and Quality initiated.	
Risk Element 8 **Facilities**	
Facility Requirements	
Facility changes initiated that are consistent with proposed LRIP production levels	
Facility personnel participants in the Integrated Product Team	

Manufacturing Readiness Level 5 Worksheet[1]	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.	
Application PEM Stacks and PEM Systems		
		Status
Risk Element 9 **Manufacturing Planning, Scheduling, and Control**		
Manufacturing Strategy and Planning		
Manufacturing plan is developed, working and being reviewed.		
Manufacturing flow chart completed.		
Subcontractor / supplier management plan in place and working		
Have alternative sources for critical components been identified?		

Appendix B
Manufacturing Readiness Assessment
MRL-6 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 6 Worksheet[1]	**Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.

Application PEM Stacks and PEM Systems		
	Status	
Thread 1 **Technology and Industrial Base**		
Technical Maturity		
Program has achieved TRL-6		
Representative prototype tested in simulated operational environment		
Components are functionally compatible with operational system		
Critical manufacturing processes prototyped		
Trade studies and laboratory experiments to define critical manufacturing processes complete.		
Successful system manufacture in pilot line demonstrated.		
Industrial subcontractors and production capacity		
Long lead time items resolved		
Contingency requirements have been evaluated and documented		
Thread 2 **Design**		
Design for Manufacturing		
Frequent design changes occur		
Does manufacturing plan evaluate the producibility of system and components?		
IPT integrates manufacturing needs into overall product plan		
System design with changes is still a low risk for manufacturing		
"Design to Cost" criteria maintained		

Appendix B
Manufacturing Readiness Assessment
MRL-6 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 6 Worksheet[1]	**Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.

Application PEM Stacks and PEM Systems	
	Status
Thread 3 **Materials**	
Material Standardization	
Material standardization plan being used	
Material Availability & Handling	
Materials available are in “production quantities”	
Initiate a parts /materials procurement plan	
Material control and inventory control processes in place.	
Environmental issues with materials addressed.	
Thread 4 **Cost and Funding**	
Design to Cost	
Design to cost goals are identified	
Detailed cost analysis is available that includes design trades and allocated cost targets	
Make / Buy assessment updated as design matures.	
Cost Drivers	
Cost center accumulates cost data and reports results on regular basis	
Cost traceable to manufacturing process steps	
Analysis of non-recurring capital and engineering costs ongoing	
Cost Reduction Plan	
Cost reduction plan operational and contributing to reducing cost	
Cost model is developed and contributing to cost reduction program.	

Manufacturing Readiness Level 6 Worksheet[1]	**Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.

Application PEM Stacks and PEM Systems	
	Status
Thread 5 **Process Capability and Control**	
Manufacturing Processes	
Progress being made toward major production related changes	
Production issues identified and major issues resolved	
Prototype process demonstrations are complete	
Special tools and tests purchased and are being installed	
Manufacturing Process Control	
Analysis of production throughput completed using pilot line	
Yield issues understood and major issues resolved	
Thread 6 **Quality**	
Quality Strategy	
Continuous process improvement program in place and working	
Quality and reliability levels established	
Sigma levels under evaluation to determine if cost targets for components/ subsystems / total system satisfied	
Supply Chain Quality	
Quality and reliability requirements flowed down to subcontractors	

Manufacturing Readiness Level 6 Worksheet[1]	**Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.

Application PEM Stacks and PEM Systems	
	Status
Thread 7 **Personnel**	
Specialty Skills & Training	
Training program necessary for specialty skills completed.	
Training programs in place for Process Control and Quality.	
Funding for training is in place	
Thread 8 **Facilities**	
Facility Requirements	
Facility changes underway that are consistent with proposed LRIP production levels	
ISO or other appropriate certification necessary is identified	
Thread 9 **Manufacturing Planning, Scheduling, and Control**	
Manufacturing Strategy and Planning	
Manufacturing plan updated and evaluated with risk plan	
Subcontractor / supplier management plan in place and working	
Critical schedule paths identified	

Appendix B
Manufacturing Readiness Assessment
MRL-7 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 7 Worksheet[1]	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production and manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Application PEM Stacks and PEM Systems	
	Status
Thread 1 Technology and Industrial Base	
Technical Maturity	
Program has achieved TRL-7	
System prototype successfully tested in a field environment	
System prototype improves to pre-production quality	
Materials and manufacturing process and manufacturing procedures initially demonstrated at pilot line	
Industrial subcontractors and production capacity	
Components are representative of production components	
Contingency requirements have been evaluated and documented	
Subcontractor production capabilities are monitored	
Thread 2 Design	
Program Performance Baseline	
Configuration management and engineering change process are in place for production and subcontractors	
Design for Manufacturing	
Design changes decrease significantly	
Technical acceptance criteria are established	

Manufacturing Readiness Level 7 Worksheet[1]	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production and manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Application PEM Stacks and PEM Systems	
	Status
Thread 2 **Design continued**	
Does manufacturing plan evaluate the producibility of system and components?	
IPT integrates manufacturing needs into overall product plan	
System design is low risk for manufacturing	
"Design to Cost" criteria maintained	
Thread 3 **Materials**	
Material Availability & Handling	
Procurement plan in place	
Make / Buy decisions have been made on critical materials / components?	
Materials available in "production quantities"	
Pre-production system hardware available, quantities may be limited	
Thread 4 **Cost and Funding**	
Design to Cost	
A detailed cost analysis is in place	
Program continues to make progress to cost goals	
Design or material breakthroughs identified to reach initial manufacturing cost	

Manufacturing Readiness Level 7 Worksheet[1]	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production and manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Application PEM Stacks and PEM Systems	
	Status
Thread 4 **Cost and Funding continued**	
Cost Drivers	
Cost center accumulates cost data and reports results on regular basis	
Costs are traceable to manufacturing process steps and monitored for future potential improvement	
Non-recurring engineering and capital costs for LRIP completed	
Cost Reduction Plan	
Cost reduction plan operational and contributing to reducing cost	
Cost model is developed and contributing to cost reduction program	
Cost mitigation plans developed	
Subcontractor and supplier cost control measures in place	
Thread 5 **Process Capability and Control**	
Manufacturing Processes	
Process tooling and inspection / test equipment demonstrated on pilot line for LRIP	
Manufacturing processes generally well understood	
Process equipment enables pre-production quality of system prototype.	
Machines and tooling proven	

Manufacturing Readiness Level 7 Worksheet[1]	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production and manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Application PEM Stacks and PEM Systems	
	Status
Thread 5 **Process Capability and Control continued**	
Manufacturing Process Control	
Maintainability, reliability, and supportability data for manufacturing processes is above 60% of total needed data	
Quality trend and failure analysis under development for continuous process control	
Yield data will be obtained from pilot line operation	
Thread 6 **Quality**	
Quality Strategy	
Sigma levels established and quality organization operating to established quality goals	
Statistical process control capability in place	
Metrology program in place for production equipment, tooling and testing calibration	
Quality program integrated with continuous process improvement program	
Quality Strategy continued	
Quality organization certify production processes and training of personnel	

Manufacturing Readiness Level 7 Worksheet[1]	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production and manufacturing process and procedures initially demonstrated. Design to cost goals validated.

Application PEM Stacks and PEM Systems	
	Status
Thread 6 Quality continued	
Supply Chain Quality	
Subcontractor and suppliers quality programs reviewed and accepted / changed	
Thread 7 Personnel	
Specialty Skills & Training	
All training programs in place and operational.	
Thread 8 Facilities	
Facility Requirements	
Facility changes near completion that are consistent with proposed LRIP production levels	
Progress made on certification	
Thread 9 Manufacturing Planning, Scheduling, and Control	
Manufacturing Strategy and Planning	
Ready for Low Rate Initial Production (LRIP)	
Production planning is complete	
Delivery schedules meet program needs.	
Internal and supplier quality programs have been developed	

Appendix B
Manufacturing Readiness Assessment
MRL-8 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 8 Worksheet[1]	**Manufacturing Process Maturity Demonstration.** Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 1 Technology and Industrial Base	
Technical Maturity	
Program has achieved TRL-8	
Manufacturing processes demonstrated at LRIP in pilot line	
Industrial subcontractors and production capacity	
Components are form, fit and function compatible with operational system	
Subcontractor production capability being monitored	
Risk Element - 2 Design	
Program Performance Baseline	
Critical product and process technologies are defined	
Design for Manufacturing	
Design stable and few or no design changes	
Technical acceptance criteria established	
Does manufacturing plan evaluate the producibility of system and components?	
IPT integrates manufacturing needs into overall product plan	
System design is low risk for manufacturing	
"Design to Cost" criteria are maintained	

Appendix B
Manufacturing Readiness Assessment
MRL-8 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 8 Worksheet[1]	**Manufacturing Process Maturity Demonstration.** Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).
Application PEM Stacks and PEM Systems	
	Status
Risk Element - 2 **Design continued**	
Tooling design plan	
Process and tooling are mature	
Risk Element - 3 **Materials**	
Material Availability & Handling	
Materials, components, and hardware are in production	
Material and inventory control system are in place and functional	
Make / Buy decisions and Bill of Materials complete and support Low Rate Initial Production	
Risk Element - 4 **Cost and Funding**	
Design to Cost	
Cost estimates a re < 125% of cost goals	
A detailed cost analysis is in place	
Program continues to make progress to cost goals	
Cost Drivers	
Cost center accumulates cost data and reports results on regular basis	
Costs are traceable to manufacturing process steps and monitored for future potential improvement	
Initiate analysis for non-recurring capital and engineering costs for Full Rate Production (FRP)	

Manufacturing Readiness Level 8 Worksheet[1]	**Manufacturing Process Maturity Demonstration.** Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 4 **Cost and Funding continued**	
Cost Reduction Plan	
Cost reduction plan operational and contributing to reducing cost	
Cost model is mature, no changes to model and model is contributing to cost reduction program	
Cost mitigation incorporated in cost reduction plan	
Subcontractor and supplier cost control measures in place	
Risk Element - 5 **Process Capability and Control**	
Manufacturing Processes	
Manufacturing processes have demonstrated acceptable yield and LRIP production levels	
Machines and tooling are proven	
Manufacturing Process Control	
Maintainability, reliability, and supportability data collection for manufacturing processes has been completed	
Quality trend and failure analysis operational for continuous process control	
Manufacturing process controlled to appropriate quality level	
Yield and quality data obtained from pilot line operation	

Manufacturing Readiness Level 8 Worksheet[1]	**Manufacturing Process Maturity Demonstration.** Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 6 Quality	
Quality Strategy	
Quality and reliability levels established	
Metrology program in place for production equipment, tooling and production testing calibration	
Quality program part of continuous process improvement program	
Quality organization certifies production processes and training of personnel	
Supply Chain Quality	
Subcontractor and suppliers quality programs reviewed and accepted / changed	
Risk Element - 7 Personnel	
Specialty Skills & Training	
Specialty skills verified on pilot line	
Training part of continuous improvement program	
Risk Element - 8 Facilities	
Facility Requirements	
Facilities in place for LRIP production	
All non-recurring costs associated with facilities documented	
Facilities LRIP certification is completed	

Manufacturing Readiness Level 8 Worksheet[1]	**Manufacturing Process Maturity Demonstration.** Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 9 **Manufacturing Planning, Scheduling, and Control**	
Manufacturing Strategy and Planning	
Operating at LRIP rate production	
Production planning and control measures in place and working	
Initiate analysis for full rate production planning and control	

Appendix B
Manufacturing Readiness Assessment
MRL-9 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 9 Worksheet[1]	**Manufacturing Processes Proven.** Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to 6-sigma or appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 1 **Technology and Industrial Base**	
Technical Maturity	
Program has achieved TRL-9	
Actual system fully demonstrated	
Stable LRIP production and meeting LRIP cost targets	
Full scale production decision made	
Risk Element - 2 **Design**	
Design for Manufacturing	
Design changes eliminated or minimized	
Major design features stable and proven in test and evaluation.	
Does manufacturing plan evaluate the producibility of system and components?	
IPT integrates manufacturing needs into overall product plan	
System design is low risk for manufacturing	
"Design to Cost" criteria maintained	
Plans in place to mitigate schedule delays	
Risk Element - 3 **Materials**	
Material Availability & Handling	
All materials are in production and readily available	
All materials meet planned low rate production schedules.	
Full rate manufacturing material needs are identified	

Appendix B
Manufacturing Readiness Assessment
MRL-9 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 9 Worksheet[1]	**Manufacturing Processes Proven.** Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to 6-sigma or appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 4 **Cost and Funding**	
Design to Cost	
LRIP cost goals and production goals met or at < 110% of cost	
Cost Drivers	
Cost center accumulates cost data and reports results on regular basis	
Costs are traceable to manufacturing process steps and monitored for future potential improvement	
Cost to achieve full rate production including non-recurring costs identified and funds requested	
Cost Reduction Plan	
Cost model developed for full rate production	
Full rate cost model includes continuous improvement	
Lean practices analysis for full rate production initiated	
Risk Element - 5 **Process Capability and Control**	
Manufacturing Processes	
Machines and tooling for full rate production under evaluation	
LRIP production risks are being monitored	
Manufacturing Process Control	
All LRIP manufacturing processes controlled to 6-sigma or appropriate quality level	
Full rate process control concepts under development	

Manufacturing Readiness Level 9 Worksheet[1]	**Manufacturing Processes Proven.** Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to 6-sigma or appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 6 **Quality**	
Quality Strategy	
Metrology program in place for equipment, tooling and testing calibration	
Quality strategy under evaluation for full rate production	
Machines, tooling and inspection and test equipment deliver or appropriate quality level in low rate production	
Supply Chain Quality	
Subcontractor and suppliers quality programs reviewed and accepted / changed	
Risk Element - 7 **Personnel**	
Specialty Skills & Training	
Plans are in place for full rate production training	
Risk Element - 8 **Facilities**	
Facility Requirements	
Non-recurring cost associated with facility requirements for FRP have been identified	
Facility upgrades to full rate production initiated.	
Facilities certification for full rate production initiated	

Manufacturing Readiness Level 9 Worksheet[1]	**Manufacturing Processes Proven.** Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to 6-sigma or appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met).

Application PEM Stacks and PEM Systems	
	Status
Risk Element - 9 **Manufacturing Planning, Scheduling, and Control**	
Manufacturing Strategy and Planning	
Operating at LRIP rate production	
Initiate analysis of full rate production throughput	
Full rate production planning and control measures under development	

Appendix B
Manufacturing Readiness Assessment
MRL-10 for PEM Pre-Automotive Applications
PEM Fuel Cell Stacks and PEM Systems

Manufacturing Readiness Level 10 Worksheet[1]	**Full Rate Production demonstrated and lean production practices in place.** The system, component or item is in full rate production. Technologies have matured to at least TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.
Application PEM Stacks and PEM Systems	
	Status
Risk Element - 1 **Technology and Industrial Base**	
Technical Maturity	
Program has achieved TRL-9	
Production products meet all engineering and functional requirements	
All system development and design targets are met.	
Stable full rate production and meeting FRP cost targets	
Risk Element - 2 **Design**	
Design for Manufacturing	
Design changes eliminated	
Does manufacturing plan evaluate the producibility of system and components?	
Low risk system design proven	
"Design to Cost" criteria met	
Risk Element - 3 **Materials**	
Material Availability & Handling	
Full scale manufacturing materials needs are met	

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Application PEM Stacks and PEM Systems	
	Status
Risk Element - 4 **Cost and Funding**	
Design to Cost	
FRP cost goals and production goals met.	
Cost Drivers	
Cost to achieve full rate production verified and allocated	
Cost Reduction Plan	
Full rate production meets cost model target	
Full rate cost model includes continuous improvement and lean practices	
Risk Element - 5 **Process Capability and Control**	
Manufacturing Processes	
Machines and tooling for full rate production installed and operational	
FRP production risks are being monitored	
Manufacturing Process Control	
All manufacturing processes controlled to 6-sigma or appropriate quality level	
Full rate process control concepts development and functional	

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Application PEM Stacks and PEM Systems		
	Status	
Risk Element - 6 Quality		
Quality Strategy		
Metrology program in place for production equipment, tooling and testing calibration		
Quality strategy in place for full rate production		
Machines, tooling and inspection and test equipment deliver or appropriate quality level in full rate production		
Supply Chain Quality		
Subcontractor and suppliers quality programs reviewed and accepted		
Risk Element - 7 Personnel		
Specialty Skills & Training		
Full rate production training completed		
Risk Element - 8 Facilities		
Facility Requirements		
Facility upgrades to full rate production in place.		
Facilities certification at full rate production in place		

Manufacturing Readiness Level 10 Worksheet[1]	**Full Rate Production demonstrated and lean production practices in place.** The system, component or item is in full rate production. Technologies have matured to at least TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.		
Application PEM Stacks and PEM Systems			
		Status	
Risk Element - 9 Manufacturing Planning, Scheduling, and Control			
Manufacturing Strategy and Planning			
Operating at full rate production			
Full rate production planning and control measures in place			

[1] Department of Defense "Technology Readiness Assessment (TRA) Deskbook", September,2003
Department of Defense MRL GUIDE 2007.
"Department of Defense, Manufacturing Readiness Assessment (MRA) Deskbook", 25 March 2008
Air Force Transition Readiness Level Calculator, Version 2.2
"Hydrogen Program Manufacturing Readiness Levels Proton Exchange Membrane Fuel Cells", DJW to MU, May, 2008
"Briefing on MRLs". M. Ulsh and D. Wheeler to Department of Energy, May, 2008

Appendix C
Manufacturing Readiness Assessment
PEM Fuel Cell Stacks and PEM Systems
Industry Interview Questions

Technical Maturity

4. Scalable technology prototypes have been produced in laboratory
5. Prototype materials, prototype components, tooling and test equipment in development for pilot line production, but manufacturing process still in development
    a. Trade studies and laboratory experiments under way to define critical manufacturing processes
    b. Subcontractors are identified
6. Trade studies and laboratory experiments to define critical manufacturing processes complete
    a. Critical manufacturing processes prototyped
    b. Successful system manufacture on pilot line demonstrated
7. Components are representative of production components; and materials, manufacturing processes, and manufacturing procedures initially demonstrated on pilot line
8. Manufacturing processes demonstrated at low rate initial production (LRIP) on pilot line
    a. Components are form, fit and function compatible with operational system
9. Stable LRIP production and meeting LRIP cost targets
    a. Actual system fully demonstrated
    b. Full scale production decision made
10. Stable full rate production (FRP); and meeting FRP cost targets

Design

4. Integrated Product Team (IPT) been formed that includes manufacturing and engineering
    a. IPT is guided by "Design to Cost" criteria
    b. The component and hardware requirements are established
5. There are significant design and engineering changes
    a. IPT has established design and manufacturing approach
    b. Configuration management process is tracking subcontractors
6. IPT integrates manufacturing needs into overall product plan
    a. "Design to Cost" criteria maintained
    b. Frequent design changes still occur
7. Configuration management and engineering change process are in place for production and subcontractors
    a. System design is low risk for manufacturing
    b. Design changes decrease significantly
8. All critical product and process technologies and their status are defined; and design is stable, with few or no design changes
9. Design changes eliminated or minimized
10. Design changes eliminated and "Design to Cost" criteria met

Materials

4. Exotic / high cost materials identified and this issue is being addressed

5. Material standardization plan developed
6. Material control and inventory control processes in place
    a. Environmental issues with materials addressed
7. Procurement plan in place and materials available in "production quantities"
    a. Pre-production system hardware is available, although quantities may be limited
8. Make / Buy decisions and Bill of Materials complete and support LRIP
9. All materials meet planned LRIP schedules
    a. FRP material needs are identified
10. Full scale manufacturing materials needs are met

Cost and Funding

4. The total system cost goals are available to the IPT and are used to guide the system design
    a. Manufacturing cost drivers identified
5. Investment needs for process and tooling are determined; and Make / Buy program initiated
    a. Cost reduction plan is operational and contributing to reducing cost
    b. Cost model is developed
    c. Subcontractors and suppliers cost control identified
6. Cost center accumulates cost data and reports results on regular basis
    a. Costs are traceable to manufacturing process steps
    b. Cost model is contributing to cost reduction program
7. Analyses of non-recurring engineering and capital costs for LRIP are completed
    a. Cost mitigation plans are developed
    b. Program continues to make progress to cost goals
8. Cost estimates < 125% of cost goals
    a. Cost mitigation incorporated in cost reduction plan
    b. Initiate analysis for non-recurring capital and engineering costs for FRP
    c. Cost model is mature, no changes to model and model is contributing to cost reduction program
9. LRIP cost goals and production goals met or at < 110% of cost
    a. Cost to achieve FRP including non-recurring costs are identified and funds are requested
    b. Cost model developed for FRP
10. FRP cost goals and production goals met
    a. FRP meets cost model target
    b. Full rate cost model includes continuous improvement and lean practices

Process Capability and Controls

4. Manufacturing State-of-the-Art identified
    a. Key manufacturing processes are identified and assessed in the laboratory
    b. Manufacturing processes that need to be developed are identified
5. Key manufacturing processes assessed for pilot line

   a. Processes that require major production-scale related changes are identified
6. Production issues identified and major issues resolved
   a. Prototype process demonstrations are complete
   b. Analysis of production throughput completed using pilot line
   c. Yield issues understood and major issues resolved
7. Process tooling and inspection / test equipment demonstrated on pilot line for LRIP
   a. Manufacturing processes generally well understood
   b. Process equipment enables pre-production quality of system prototype
   c. Maintainability, reliability, and supportability data for manufacturing processes is above 60% of total needed
8. Manufacturing processes demonstrate acceptable yield
   a. LRIP production levels achieved; and maintainability, reliability, and supportability data collection for manufacturing processes has been completed
   b. Manufacturing process controlled to appropriate quality level
   c. Quality trend and failure analysis operational for continuous process control
9. All LRIP manufacturing processes controlled to 6-sigma or appropriate quality level
   a. Machines and tooling for FRP under evaluation
10. Machines and tooling for FRP installed and operational
   a. All manufacturing processes controlled to 6-sigma or appropriate quality level

Quality

4. Continuous process improvement program in place and working
   a. Metrology program in place
5. Quality and reliability levels established
   a. Quality and reliability requirements flowed down to subcontractors
6. Quality organization operating to established quality goals
   a. Metrology program is in place for production equipment, tooling and testing calibration
   b. Statistical process control capability in place
      i. Subcontractor and suppliers quality programs reviewed and accepted / changed
7. Quality and reliability levels established
   a. Quality program part of continuous process improvement program
8. Machines, tooling, and inspection and test equipment deliver appropriate quality level at LRIP
   a. Quality strategy under evaluation for FRP
9. Machines, tooling, and inspection and test equipment deliver appropriate quality level at FRP
   a. Metrology program in place for production equipment, tooling and testing calibration
   b. Quality strategy in place for FRP

Personnel

4. Training programs necessary for specialty skills identified
    a. Training programs identified for process control and quality
6. Funding for training is in place
    a. Training program necessary for specialty skills and for process control and quality in place
7. All training programs in place and operational
8. Specialty skills verified on pilot line
    a. Training part of continuous improvement program
9. Plans in place for FRP training
10. FRP training completed

Facilities

4. Non-recurring costs associated with facility requirements are documented
    a. Facility resource requirements are documented
5. Facility changes initiated that are consistent with proposed LRIP production levels
6. Facility changes underway that are consistent with proposed LRIP production levels
7. Facility changes near completion that are consistent with proposed LRIP production levels
8. Facilities in place for LRIP production; and facilities certification for LRIP is completed
    a. All non-recurring costs associated with facilities documented
9. Identified non-recurring cost associated with facility requirements for FRP
    a. Facility upgrades to full rate production initiated
    b. Facilities certification for FRP initiated
10. Facility upgrades for FRP in place; and facilities certification for FRP in place

Manufacturing Planning, Scheduling, Control

4. Manufacturing strategy developed
    a. A manufacturing control hierarchy is in place
5. Manufacturing plan is developed, working, and being reviewed; and manufacturing flow chart completed
6. Manufacturing plan updated and evaluated with risk plan; and critical schedule paths are identified
7. Production planning is complete; ready for LRIP
    a. Delivery schedules meet program needs
8. Operating at LRIP rate production
    a. Initiate analysis for FRP planning and control
9. FRP planning and control measures under development; and initiate analysis of FRP throughput
10. Operating at FRP; and FRP planning and control measures in place

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