Final Report
Propane Oriented Issues
for
Fuel Cell Assessment
Volume I of II

Submitted to

Propane Education & Research Council
Docket 11071

Submitted by

Spencer Management Associates
National Fuel Cell Research Center
R4Energy, Inc.

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1 Executive Summary

The Propane Education & Research Council (PERC) contracted with Spencer Management Associates to examine fourteen pertinent issues with respect to Propane and fuel cell technology. Spencer Management assembled a team designed to provide independent expert analysis and consultation that consisted of,

Dr. Jack Brouwer	Associate Director	National Fuel Cell Research Center, University of California - Irvine
Mr. Robert Wichert	Engineer	R4Energy, Inc.
Mr. Byron Washom	President	Spencer Management Associates

The key findings for each of the tasks reflect the past three years of relatively slow progress in the commercialization of stationary fuel cells that utilize propane as the primary fuel source. This report reflects the more current public information from the November 2005 Fuel Cell Seminar which is the largest fuel cell seminar in the world, and the forum where most manufacturers published their significant technical findings. The delay in this final report has benefited from the ability to garner some kernels of optimism for propane fuel cells, and in the interim, PERC has prudently and cautiously supported propane related fuel cell research and demonstration on a limited basis. The extra time has also provided signals of expanding support from The World Bank, the G8 "Gleneagles Initiative" and the extremely strong Japanese market-pull and technology-push for propane fueled systems. As reported herein, the World Bank Group's International Finance Corporation made its first grant to Plug Power for telecommunication and remote power applications in South Africa, and Kuwait announced its support to a $100M R&D program with ARAMCO for on-board reforming despite DOE's abandonment of this strategy in 2004. The additional time also provide clarity from public forums of Delphi's modest efficiency gains in its DOE recreational vehicle APU program and Cummins Power Group decision to pursue diesel, rather than the original plan of propane, for their long haul truck APU program with DOE.

The key findings are summarized below and detailed in the body of the report.

1. Assessment of Past and Present PERC Fuel Cell Activities

Byron Washom made presentations to PERC's Board of Directors on October 4, 2004 and the Texas Railroad Commission Propane Energy Conference on August 5, 2005. Additionally, he provided advisory services to the Research committee on proposals from Plug Power, IdaTech/Cummins and HARC.

Dr. Jack Brouwer of NFCRC reviewed and assessed approximately 100 pages of PERC's fuel cell activities to date, including pending, completed, and ongoing projects. The team has consequently recommended steps that PERC can take to improve the effectiveness and efficiency of funding allocated to advance the development of propane fuel cells. The potential of fuel cell technology is significant and rapidly proving itself. This rapidly advancing fuel cell technology will impact and change the propane market, and indeed may depend upon the propane community to succeed especially in remote power (or recreational power), back-up power (or uninterruptible power), and portable power (or auxiliary power) market segments. The following bulleted list summarizes the findings of the current study:

- Propane will not likely be used to any significant degree in automotive fuel cell applications of the future.

- Potential niche automotive applications are more likely with hydrogen refueling that is based propane reformation technology, which may be applicable to some remote re-fueling locations.

- The much more likely widespread application of propane fuel cell technology is in the small stationary power markets, such as remote back-up power, uninterruptible power supplies, residential co-generation (e.g., as in Japan), and in the longer term, the RV and truck long haul auxiliary power unit s(APU).

- The advancement of flexible, high power density, low cost and efficient propane fuel processing technology is what is primarily required to facilitate the early introduction of fuel cell technology especially in the remote power and backup power sectors.

- Regulatory, safety, and policy understanding and the general acceptance of and consumer comfort with propane fuel may contribute to the general acceptance of fuel cell technology for remote power, backup power, and APU markets.

- The technical features and capabilities that a propane reformer-based fuel cell product may be able to offer (remote re-fueling, higher fuel energy density, acceptable storage standards/policies, longer back-up power supply, additional on-board power and electrical features, recreational power, etc.) might significantly advance consumer acceptance of fuel cell technology.

- A significant challenge for all fuel cell fuel processing technology is the removal of sulfur, which poisons many reformer and fuel cell catalysts. Most groups are removing sulfur through an absorption or adsorption bed of either an activated carbon or zinc-oxide. These beds have proven effective, but, the capturing all of the sulfur compounds that can be present in propane is a challenge and the logistics of bed replacement or re-generation are challenging.

- Propane can be electrochemically oxidized directly in a fuel cell system, instead of using a fuel processor. The direct electrochemical oxidation of propane in a solid oxide fuel cell is an attractive long-term option worthy of consideration and one that is currently being advanced by several organizations.

- Both PEMFC and solid oxide fuel cells (SOFC) will continue to require some type of fuel processor for cost effective early introduction to the marketplace. These fuel processors will likely require significant integration with the fuel cell itself, leading to the need for PERC to work closely with fuel cell manufacturers and fuel cell systems integrators in important near-term application areas.

- This report for PERC has uncovered at least 20 organizations around the world that have tested fuel processing technology on propane, which is promising.

- By far the most significant challenge for propane fuel processing and fuel cell systems in general is associated with cost reduction and the ability to produce

viable and reliable fuel processor-fuel cell systems at a cost that is low enough to compete in the marketplace.

- The PEMFC market foci on APU and back-up power applications, where propane use as a fuel may have some distinct advantages compared to other energy carrier solutions, are promising market foci for PERC to consider.

The team compared the overall current and likely future direction of the fuel cell industry (i.e. types of equipment developed and under development, capacity, markets addressed, etc.) with the projects that PERC has funded or is currently funding. The primary observations were that the Japanese PEM developers are far more engaged in residential propane applications and more advancement in reformer technology than any North American PEM developer. The DOE solid oxide fuel program (SECA) has a greater, long term potential for stationary and APU applications using propane fuel. A word of caution though, the UPS and backup power market applications, regardless of fuel cell technology, does not represent a particularly large source of propane demand due to limited hours of application per year.

2. Acceleration of Commercialization

Spencer Management determined whether a new or revised PERC funding strategy can accelerate commercialization of propane-powered fuel cells and make recommendations based on such determination. We concur with the current proposal before PERC to continue to communicate with the fuel cell industry, monitor the cost and performance of developing systems to see when and if US demonstrations make sense; continue to focus propane research dollars on fuel filtering / sulfur removal, and on the reforming / processing of propane fuel; track the best developing technologies for potential residential applications based on cost, net electrical efficiency, and durability; monitor DOE vehicular hydrogen refueling station funding programs for opportunities to advance propane reformer development for stationary FC applications; conduct demonstrations as significant new technologies are available; require significant co-funding for future projects from DOE, DOD's Civil Engineering Research Laboratory (CERL) , manufacturers and others; and consider a PERC RFP for FC demonstration projects only when fuel cells become competitive with generator systems. The primary additional recommendation would be to significantly increase the interaction and participation with Japanese PEM fuel cell developers since their programs are more advanced and better funded with respect to propane reforming since propane is a fuel of choice for many Japanese residential applications. Strategic alliances and cooperations with targeted Japanese companies for US field demonstrations of propane fueled PEM systems would be a higher priority than PERC considering investment of non-propane related fuel cell development, e.g. balance of plant R&D. At the encouragement of Spencer Management, both Toyota and Nippon Oil made well received, propane oriented presentations to PERC members in Austin, Texas in the summer of 2004. The second recommendation is to cooperate more closely with planar solid oxide fuel cell program that is being managed by the National Energy Technology Laboratory (NETL) within the U.S. Department of Energy. The long term, high risk, high payoff program has goals of $400/kW, 40-60% efficiency, 40,000 hrs operating life and multi-fuel operations.

3. Assessment of Reformer Free Fuel Cell Technology

Dr. Jack Brouwer of NFCRC addressed the relative likelihood that a reformer free fuel cell technology is a realistic option for PERC funding consideration. Dr. Brouwer's conclusion was that the reformer-free fuel cell was highly speculative and limited resources are currently being spent in this area and for good reason. Therefore, it is the conclusion of the team that PERC should not predicate or speculate on the commercialization of a reformer free fuel cell in the foreseeable future.

4. Leverage with bidders to DOE's Recreational Vehicle APU Program

DOE was unresponsive to any discussions of leveraging or cost sharing with the winning bidders while the proposals were being evaluated. When the winning bidders of Delphi and Cummins with their planar solid oxide fuel cell design were announced, it became evident that an organizational conflict of interest existed for Spencer Management Associates. SMA serves as DOE's external reviewer of Delphi and Cummins for DOE NETL; therefore, SMA could not serve DOE in this critical and proprietary capacity and simultaneously be promoting Delphi and Cummins to work with its other client in PERC. The compromise was to alert Mr. Steven Shaffer and Dan Norrick, the program managers at Delphi and Cummins respectively, of PERC's interests in fuel cell, and for these parties to develop a dialogue independent of SMA. This interest was re-communicated to Delphi and Cummins at the Annual Fuel Cell Seminar in San Antonio TX in August, 2004 and Palm Springs CA in November 2005.

The DOE program is a $9M, 3 year, 3 contractor R&D effort by DOE for recreational vehicles and truck refrigeration that included development, construction, and validation of propane powered fuel cell power systems for APU applications. This scope included a very relevant power range of 3-5 kW average/5-10 kW peak for APUs on recreational vehicles and a less relevant 10-30 kW for refrigeration for long-haul trucks. The RFP required that the technology to operate on hydrogen or hydrogen derived from on-board processing of propane or low-sulfur diesel fuel, depending on the application and type of fuel cell.

In a paper presented at the 2005 Fuel Cell Seminar, revealed the Delphi system development to date has successfully completed the system integration of a Stationary Power Unit comprised of methane CPOx reformer, 2 x 30-cell Gen 3 stacks, electronic controller and control software, power electronics, and BOP components. The system is a complete SOFC system capable of automatic cold-start-to-run operation and internal 42 VDC and 12 VDC power bus support. The system has direct DC output, with an optional AC inverter employed for AC electrical loads. This system was designed to support up to 3 kW net electrical output at 18% efficiency, with future upgrades allowing up to 35% efficiency.

A paper presented at the 2005 Fuel Cell Seminar by James Butcher of Cummins Power Group indicated that their SOFC APU for a Class 7/ Class 8 Truck has pursued a diesel based, fuel cell rather than propane due to previous market rejection by both fleet and independent owners on a second source of fuels. Due to difficulty and challenges with respect to start time, ramp rate (ability to increase output to support additional load) and impact on storage battery size and life, control strategy, fuel reformation and water control, shock an and vibration Isolation, durability in real world mobile applications, and total system cost, PERC can anticipate a longer than anticipated R&D schedule in this diesel based APU program. The transition to propane APU fuel cells at the RV and long haul truck markets would presumably follow the diesel program. Butcher also noted that,

> The limited success of today's APU's in the line haul truck market can be directly attributed to the failure of these products to address the critical combination of function and cost necessary to earn their way in the highly competitive trucking industry. Today's truck owners are looking for a payback on their investment of less than 18 months, and with high installation costs and historically lower fuel prices, the equation has not balanced.

In a November 28, 2005 email to Spencer Management Associates in support of this PERC report, Dan Norrick of CPG noted that,

> CPG began our SECA program focused on LPG as a fuel that could potentially be acceptable to the RV market for use in fuel cells. It was less of a challenge to reform, and was being carried on RV's. We shifted our SECA focus to natural gas in response to DOE's direction to test on natural gas, and have shifted our longer range focus to diesel based on progress we see with diesel reforming and the desire for many mobile applications to run on diesel fuel. We recognize that longer term it is probable that we will want to operate on all three fuels (diesel, LPG, natural gas) to cover all the potential applications, but diesel will be a key fuel to support the quickest market acceptance.

Therefore, it does not appear that Cummins Power Group will represent a modest near term collaboration opportunity; however, the exceptional forthright discussion of the technical and market challenges to on-board, truck long haul fuel cell APUs should be closely studied for any potential APU co-funding.

5. Nippon Oil's 100 Unit Propane Fuel Cell Demonstration Program, 2003-05

For the past three years, Spencer Management has been advocating closer ties with the Japanese PEM developers, particularly Nippon Oil Company and Toshiba. Data supplied by Nippon Oil to Spencer Management Associates in August 2006 indicated that $60M/year of propane fuel cell leasing is current ongoing or planned in Japan with propane fuel. This represents 23% of the national total of $260M/year. Kerosene fueled systems represents another $60M, or 23%, and City Gas represents $100M/year, or 54%. There are total of 611 LPG units under lease contract, 75 kerosene units under lease contract and 491 city gas units under lease contract. All of the leased units for LPG and Kerosene are with Nippon Oil as the principal supplier, and Tokyo Gas is the principal supplier for the city gas units.

Nippon Oil has developed four different catalysts for use in kerosene and propane fuel cells applications, and has one of the largest propane fuel cell demonstrations programs in the world. Over 100 units have been installed in unit sizes of 750 W (in collaboration with Sanyo), 1 kW (in collaboration with Ballard) and 1-10 kW (kerosene fueled, in collaboration Mitsubishi Heavy Industries). At the 2005 Fuel Cell Seminar, Spencer Management reiterated PERC's interest in receiving one or more of the Nippon units for field testing in the US. Nippon Oil is grateful for the continued interest in all of their propane related products, but they remain undecided as to when they will be releasing their fuel cell systems for testing outside of Japan. Nippon Oil recently reported 34% AC electrical efficiency, 76% total efficiency in the CHP configuration for their 750W propane fueled unit. They also reported a catalyst life of 40,000 hrs which is outstanding compared to their competitors. In August 2006, Nippon Oil reported that they had entered with Japan Energy Corp. (J-Energy) for residential, propane fueled, fuel cells on an OEM basis starting in 2007. The cumulative sales are projected to reach a market-leading 435 units by the end of the fiscal year, based on

figures compiled by the Ministry of Economy, Trade and Industry. J-Energy now leases LPG fuel cells made by Toshiba Corp. (TSE:6502). With estimated aggregate sales of 63 units at fiscal year-end, the firm will be No. 4 in the market - behind Nippon Oil, Tokyo Gas Co., and Osaka Gas Co. In the alliance, Nippon Oil will supply J-Energy with the fuel cells made by Sanyo and Ebara Ballard. Nippon Oil and J-Energy aim to cut costs by leveraging their pooled orders. The arrangement will also expand J-Energy's lineup to include kerosene fuel cells.

Table 1 Characteristics of the Japanese Residential Fuel Cell Market (2006)

Fuel type	LPG	Kerosene	City Gas
Principal suppliers	Nippon Oil	Nippon Oil	Tokyo Gas
Japan Energy	Osaka Gas		
Idemitsu	Toho Gas		
(10 companies)	(6 companies)		
FC makers		Ebara Ballard	Matsushita
Ebara Ballard	Sanyo Toshiba		
Sanyo			
Price of leasing	$ 60 M/ year	$ 60 M/ year	$ 100 M/ year
(Nippon Oil)	(Nippon Oil)	(Nippon Oil)	
Estimated Sales Units	611 Units	75 Units	491 Units

Byron Washom shared the podium at the 2005 Fuel Cell Seminar with Dr. Kazuo Koseki who is head of the Japanese Fuel Cell Development Information Center and renewed PERC's.

Toshiba International continues to make strong progress towards their PEM city gas/LPG fuel cell for the Japanese market as well. At both the 2004 and 2005 Fuel Cell Seminar, Toshiba reported AC electrical efficiencies of greater than 37% (LHV) and total efficiencies of 77% for their 700 W residential units. Toshiba International has been developing resident PEM systems since FY2000. More than 50 units have been demonstrated, cell stack durability and stability of more than 9000 hours in full stack has been achieved, and decay rates of 2mV/1000 hr have been published by Toshiba. Toshiba reported in 2004 that, the PEM system is, "superior to Gas Engine based CHP systems for power efficiency and operational flexibility, but it consumes some energy for start-up and idling. Therefore, it is recommended to operate 24 hours continuously with the load following mode to maximize energy savings." Large scale field testing of 100 residential units in 2005-06 is definitely planned. One field unit was operated for 4200 hours without any unscheduled maintenance.

6. Leverage PERC R&D with Existing Partnerships and Alliances

The team presented the priority R&D portfolio to the fuel cell community and NFCRC 35 members and, we encouraged consideration of teaming, and we sought potential partners for PERC projects and proposal opportunities that could dramatically increase the leveraging

of PERC funded projects. Contained herein are the companies that are currently developing propane-powered fuel cells and their status with respect to commercialization. Reported herein is advice as to which companies PERC should be partnering as well as a determination of the technical issues specifically related to propane that must be addressed with a recommendation as to the companies that possess the expertise and disposition to address these issues. The primary recommendations are again Nippon Oil, Toshiba and Plug Power.

7. R&D Opportunities in BOP Cost Reduction

It was mutually agreed that the Balance of Plant (BOP) for small fuel cell systems typically represents 40-60% of the total installed cost of a fuel cell system. This fact has remained prevalent over the last five years, and the rate of cost of reductions in BOP has been slower than that in the fuel cell stack: thus, any gains in BOP will accelerate the rate of commercialization. Specific opportunities for the reduction in BOP did arise, Spencer Management reports herein on potential co-funding or receiving the research results on a timely basis. The primary opportunities are with the inverter, monitoring, start-up/shut down control logics, and fuel processors for the Core Technologies Program under the DOE SECA program, and the best contact is Mr. Donald Collins at the National Energy Technology Laboratory (NETL) in Morgantown WV. His contact information is 304-285-4156 and wayne.surdoval@netl.doe.gov .

8. Organizations Developing Propane-Oriented Codes, Standards and Practices

The proposed support for the development of propane oriented, standards and practices for fuel cells was decided by PERC to not be pursued in this Phase of the contract. It was recommended that PERC consider joining the US Fuel Cell Council (USFCC) for $4,000 and directly participate in their update of the USFCC modifications to the LPG, Specifications and Test Methods Committee, but this recommendation was not acted upon. In June 2004, USFCC published the first ever "Literature Survey of Fuel Cell Contaminants," to serve as a ready-access data tool to the fuel cell industry and other interested groups. The report focuses upon the effects of contaminants on the performance and components of proton exchange membrane (PEM) fuel cells, including direct methanol fuel cells (DMFC), and components. The literature survey was conducted by the Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) for the US Fuel Cell Council Materials and Components Working Group. The report features a summary of sources of contamination for water, hardware, and gas reactants, followed by more than 115 tables summarizing the government and commercial literature surveyed.

Co-author Robert Wichert of the team did provide an overview of the present national and international standards setting efforts, and the synopsis appears in the Appendices. Also in the appendix is the colloquy between Larry Osgood on behalf of PERC and Robert Wichert on the primary findings from the US Fuel Cell Council has considered work to develop propane standards for fuel cell systems, more stringent than standards currently in place. Specifically the Power Generation Working Group has investigated propane standards that would restrict constituents as found in Table 2.

Table 2 US Fuel Cell Council's Proposed Propane Standards

LPG Constituent	Suggested Specification
C3H8	>90%
C3H6	<5%
C4H10	<1%
C4+	<0.1%
Balance	C2H6 or C3H8
CO2	<0.1%
COS	<100 ppbv
H2S	<100 ppbv
C2H5SH	25 to 35 ppmv

9. State Incentive Programs to Accelerate Fuel Cell Commercialization

When the fuel cell technology matures, it will not enter a level field of play, particularly in the remote and rural applications. Competing technologies such as photovoltaics and small wind systems have, and will continue to have, significant financial, tax and regulatory incentives that will elevate their competitiveness with alternatives, including fuel cells using propane. Early commercialization of fuel cells will likely occur in those states that have the greatest financial, tax and regulatory incentives provided to an end-user, e.g. 34 states now have fuel cells eligible for net metering, up from seven in 2001. The team believes it is essential that PERC become cognizant of the incentives at the state level, and work to expand the eligibility of fuel cells wherever possible. The report provides herein to PERC the information necessary to allow PERC and its members to pursue these opportunities.

Byron Washom's plenary session paper at the 2005 Fuel Cell Seminar was entitled "World Bank and US State Programs for Commercializing Fuel Cells". It was noted that the sum of the US State Incentive Programs exceed the US federal stationary fuel cell budget, and that clearly the emphasis must now shift to manufacturing capacity. The primary pre-commercial incentives by the states are oriented towards Production and Employment Retention Grants, Loans and Grants, Rebates, Price Incentives, Net Metering, Tax Incentives, Tax Exempt Financing, and Property Tax Exemptions.

The report contains an interesting chart of three publicly traded companies responding to technology push of the US House of Representatives passing to a 30% Energy Tax Credit up to $1000/kW (7/28/05) and President Bush signing the Energy Policy Act (8/8/05) coupled with the market pull for distributed generation as a result of a Category 4 Hurricane Katrina (8/29/05) and a Category 3 Hurricane Rita (9/24/05). The net result of these extremely favorable events for fuel cells was that the three publicly traded companies returned to their original trading ranges within 2.5 months of the first stimuli. The conclusion that can be drawn from this series of events is that the sober fuel cell investor community may be awaiting evidence of a truly commercial fuel cell that can serve the distributed generation market demand in a competitive and long term fashion.

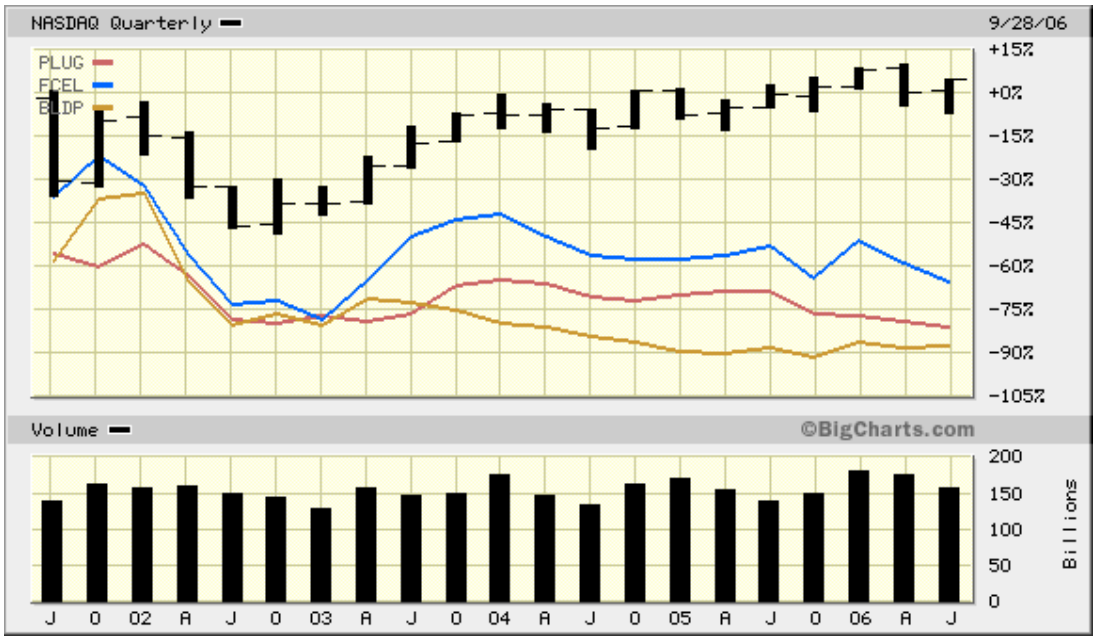
10. Market Capitalization of Publicly Traded Fuel Cell Companies

The market capitalization of publicly traded fuel cell companies witnessed significant changes over the five years when publicly traded fuel cell stocks had a dot.com like trading activity at the turn of the decade. The current market capitalization of the three major stationary fuel cell companies range from a low of $360M for Plug Power to a high of $654M for Ballard. More importantly, the share price-to-cash flow ratio are all negative with Ballard leading the way at -19.8 and FuelCell Energy with the least unattractive value at -6.10. Clearly, the sizzle is out of the speculating on fuel cell stocks, and it is now incumbent for these companies to convince investors that they can produce a commercially viable product for a price, performance and warranty that the mid- and long-term market place demands. Plug Power did announce in April 2006 and agreement for a $216M capital infusion from long term strategic investors who are Russian suppliers of platinum and palladium.

Table 3 Market Profiles of Publicly Traded, Stationary Fuel Cell Companies

	Trading Symbol	Market Capitalization $M, 9/29/2006	Share Price – to – Cash Flow Ratio
Ballard	BLDP	654	-19.80
FuelCell Energy	FCEL	418	- 6.10
Plug Power	PLUG	360	- 7.20

Figure 1 Past Five Years of Publicly Traded Stationary Fuel Cell Stocks (2001-2006)



Three major stationary fuel cell companies that are public traded were selected to portray the investment interest in fuel cells and their current operating profitability and cash flow. The three companies were Plug Power (PLUG) with a small scale stationary PEM fuel cell, FuelCell Energy (FCEL) with a .25 to 1 MW molten carbonate system and a 2-10 kW solid oxide system under development, and Ballard (BLDP) with their 1-3 kW PEM stationary fuel cell system and one of the largest transportation fuel cell programs outside of the Big Five automotive companies. The Figure 1 graphic indicates that all three companies

are trading between 65 to 88% below their stock prices five years earlier while the baseline NASDAQ is trading about 5% above.

11. Lessons Learned from Rural Electric Cooperatives in PEM Fuel Cells

As an option to the proposal, Spencer Management offered the services of Mr. William Cetti, President of ECO Technology Solutions. For the period 1999-2003 Mr. Cetti has been actively engaged in "market pull" ($80M contingent purchase order to H Power) and "technology push" (end-user specifications and demonstration sites) for the rural electric cooperatives. Spencer Management believed that PERC would be greatly served to receive and consider what went wrong and what went right with the electric cooperatives' efforts to penetrate the rural and remote markets with the H Power PEM fuel cell. Despite our best efforts to coordinate a meeting with Mr. Cetti, a convenient schedule to all parties was never established.

12. Validated Model for Competitive Price Assessments in DG Applications

The team provided guidance for PERC to download a validated model HOMER (http://www.nrel.gov/homer/) for the National Renewable Energy Laboratory (NREL) that conducts competitive price assessment that simplifies the evaluations of design options for off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. The program has over 12,000 users worldwide. HOMER's optimization and sensitivity analysis algorithms permit an end user to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. HOMER models both conventional, renewable energy and fuel cell technologies. Spencer Management reviewed the features of this model with respect to recommending it to PERC members, and strongly endorses the model for any detailed analysis that they may wish to undertake in the future.

13. Global Propane Fuel Cell Demonstration Programs

Regarding propane fuel processing and system demonstration, the current effort has uncovered at least twenty organizations around the world that have tested fuel processing technology on propane. While these organizations have met with varying degrees of success and while some are far from proving that integration into a robust fuel cell system is feasible, this level of effort is encouraging and impressive suggesting that the use of propane in future fuel cell systems is likely. Of these twenty organizations, two in particular are recommended for potential collaborative efforts, and they are Nippon Oil and Toshiba. Previously, Toyota was regarded as a possible third candidate, but the recent retrenchment by Toyota is interpreted as a possible delay in their previously aggressive program for stationary PEM fuel cells.

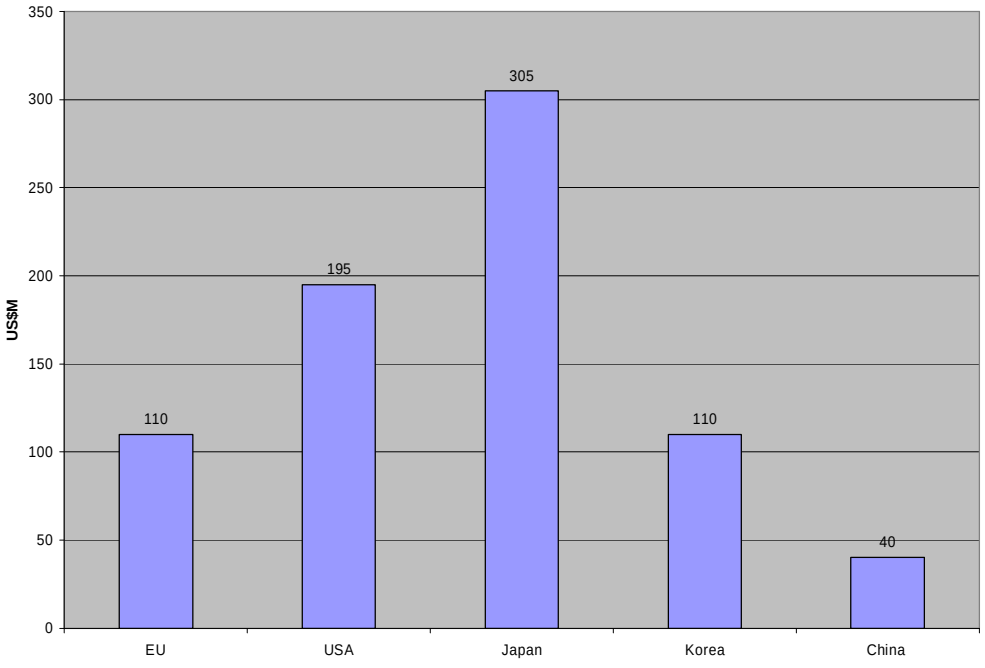
Spencer Management's paper on "Overview of Global Fuel Cell Markets & Technology with Respect to Propane" was accepted by the WLPG Technology Conference and will be presented on October 20, 2006 in Chicago. The paper noted that the existing and planned emphasis on the developing country markets by the G8, World Bank and the Asia Pacific Partnerships makes it a reasonable forecast to be the early market adopter markets due to the availability of capital buy down subsidies and higher avoided cost of energy. It is believed that the regions in the OECD countries that are currently served by propane and not served by natural gas represent a promising, economically driven market for propane fuel cells from the

"early adopter" stage to full commercialization. The existing propane supply and storage infrastructure represents a long term bridge to commercialization until onsite hydrogen is feasible, but this infrastructure remains undervalued by the majority of the fuel cell technologists due to the overshadowing fuel processing challenges associated with propane, especially when used with PEM fuel cell technology. By far the most significant challenge for propane fuel processing and fuel cell systems in general is associated with cost reduction and the ability to produce viable and reliable fuel processor-fuel cell systems at a cost that is low enough to allow competition with the existing and increasingly efficient and clean competing technologies.

14. Global Funding for Fuel Cells

The team spent a modest effort to report in a macro sense on the areas that the majority of government and private funding is being allocated and is planned to be allocated. In a paper at the 2005 Fuel Cell Seminar, David Jolie, the Editor of Fuel Cell Today, presented the below estimates of the funding by the major central governments. Figure 2 indicates a total level of effort of US$760M/yr with Japan being the largest single funding source at $310M. It is estimated that the private sector is placing at least an equal amount into fuel cell R&D, and the state governments within the US have provided at least DOE's total of $190M in fuel cell incentives.

Figure 2 Estimated Funding for Fuel Cells by Central Governments



In summary, the team believes that regions currently served by propane and not served by natural gas present a promising, economically driven market for propane fuel cells from the "early adopter" stage to full commercialization. The existing propane supply and storage infrastructure represents a long term bridge to commercialization until onsite hydrogen is feasible, but this infrastructure remains undervalued by the majority of the fuel cell technologists due to the overshadowing fuel processing challenges associated with propane,

especially when used with PEM fuel cell technology. The most significant challenge is associated with the sulfur content of the propane. Sulfur compounds present in propane poisons the fuel cell anode and in some cases damages the reforming catalyst.

The primary question is, "Given the Japanese LPG fuel cell thrust and the fact that PEM fuel cells cannot tolerate sulfur, what is the likelihood that leveraged PERC R&D funding can achieve aggressive commercial cost and performance specifications for an on-board or on-site propane fuel processing reformer?" The answer is that major Japanese corporations with world class chemical engineers have focused extensively on propane based fuel cells systems and have publicly reported impressive technical achievements for stationary PEM fuel cells.

In addressing the primary question, it will necessarily answer secondary questions of, "If propane fuel processing technology commercialization is feasible, are there financially strong and commercially viable PEM fuel cell fuel processor developers that will direct their product to the propane oriented markets of remote power, rural power and recreational vehicles due to PERC's leveraged R&D funding and/or market potential?" The answer to the second question is definitely, particularly in Japan's residential market.

Fuel cell technology is poised to significantly contribute to meeting stationary power, portable power and transportation energy needs in the near future. Recent technology advances, market penetration success, and policy initiatives portend an exciting future for fuel cell technology. Although most of the recent success has neither directly involved the use of propane in fuel cells nor demonstrated propane reformation technology, the potential of fuel cell technology to impact and change as well as depend upon the propane community is significant.

It is not likely that propane will be used to any significant degree in automotive fuel cell applications of the future. Potential niche automotive applications are more likely with hydrogen refueling that is based on propane reformation technology, which may be applicable to some remote re-fueling locations. The much more likely widespread application of propane fuel cell technology is in the auxiliary power unit (APU) and small stationary power markets, such as remote back-up power, uninterruptible power supplies, and residential co-generation (e.g., as in Japan).

The advancement of flexible, high power density, low cost and efficient propane fuel processing technology is what is primarily required to facilitate the early introduction of fuel cell technology especially in the remote power and backup power sectors. This will likely be accomplished by early introduction of propane fuel cells into the back-up power, uninterruptible power supply (UPS), and auxiliary power unit (APU) markets. IF this introduction could be accomplished with very inexpensive fuel processing technology, it could address the primary challenges of hydrogen storage (low energy density, high cost, safety concerns, consumer acceptance) that plague current fuel cell applications in these markets.

Regulatory, safety, and policy understanding and the general acceptance of and consumer comfort with propane fuel may contribute to the general acceptance of fuel cell technology for remote power, backup power, and APU markets. The technical features and capabilities that a propane reformer-based fuel cell product can offer (remote re-fueling, higher fuel energy density, acceptable storage standards/policies, longer back-up power supply, additional on-board power and electrical features, power while camping, etc.) might significantly advance consumer acceptance of fuel cell technology in general.

Propane fuel processing technology could also play an early and long-term role as a more general stationary power fuel processor (especially in remote and back-up applications, and more generally in developing countries where fuel infrastructure is scarce and the need for new installed power generating capacity is greatest). The need for propane fuel processing technology could be great regardless of fuel cell type or fuel type. Both PEMFC and solid oxide fuel cells (SOFC) will continue to require some type of fuel processor for cost effective early introduction to the marketplace (until there is a significant penetration of the hydrogen economy – perhaps 50-100 years off). These fuel processors will likely require significant integration with the fuel cell itself, leading to the need for the Propane Education & Research Council to work closely with fuel cell manufacturers and fuel cell systems integrators in important near-term application areas.

A significant challenge for all fuel cell fuel processing technology is the removal of sulfur, which poisons many reformer and fuel cell catalysts. Most groups are removing sulfur through an absorption or adsorption bed of either an activated carbon or zinc-oxide. These beds have proven effective, but the capturing all of the sulfur compounds that can be present in propane is a challenge, and the logistics of bed replacement or re-generation are challenging.

Propane can be electrochemically oxidized directly in a fuel cell system, instead of using a fuel processor. The direct electrochemical oxidation of propane in a solid oxide fuel cell is an attractive long-term option worthy of consideration and one that is currently being advanced by several organizations. In the short-term propane use in fuel cell systems requires a propane fuel processor (for use with either a PEM or SOFC). In this case, several fuel cell and fuel processor organizations have already proven the feasibility of processing propane sufficiently for use in fuel cell systems. Although this technology still needs some technical advancement, in particular focused on integration of propane fuel processors into efficient and robust complete fuel cell systems, propane reformer fuel cell systems investments should include demonstrations of the technology aimed at commercial prototypes and eventually commercial products.

By far the most significant challenge for propane fuel processing and fuel cell systems in general is associated with cost reduction and the ability to produce viable and reliable fuel processor-fuel cell systems at a cost that is low enough to allow competition with the existing and increasingly efficient and clean competing technologies.

Fortunately, the current fuel cell market, especially that for PEMFC systems, is focused on residential and back-up power applications where propane use as a fuel may have some distinct advantages, compared to other energy carrier solutions. PERC should focus its short term research and development on the advancement of propane fuel cells for residential and back-up/remote power applications. PERC should focus its mid-term focus on the SECA SOFC co-funding opportunities, and PERC should focus its longer-term research efforts on the direct electrochemical oxidation of propane in solid oxide fuel cell systems.

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2 PERC Program Issues

2.1 Assessment of PERC Funded Research

Representatives from the Spencer Management team from the National Fuel Cell Research Center (NFCRC), and R4Energy (R4Energy) have over 30 years of combined experience in developing, managing and assessing complex fuel cell R&D programs that are inter-related with parallel and competing projects around the world. PERC provided for review confidential documentation of the pending, completed and ongoing projects were reviewed and analyzed prior to the October 7, 2004 meeting.

2.1.1 Assessment of PERC Funded Research

Review and assess PERC fuel cell activities to date, including pending, completed, and ongoing projects. Recommend steps that PERC can take to improve the effectiveness and efficiency of funding allocated to advance the development of propane fuel cells. Compare the overall current and likely future direction of the fuel cell industry (i.e. types of equipment developed and under development, capacity, markets addressed, etc.) with the projects that PERC has funded or is currently funding.

Dr. Jack Brouwer of NFCRC reviewed and assessed approximately 100 pages of PERC's fuel cell activities to date, including pending, completed, and ongoing projects. The team has consequently recommended steps that PERC can take to improve the effectiveness and efficiency of funding allocated to advance the development of propane fuel cells. The potential of fuel cell technology is significant and rapidly proving itself. This rapidly advancing fuel cell technology will impact and change the propane market, and indeed may depend upon the propane community to succeed especially in remote power (or recreational power), back-up power (or uninterruptible power), and portable power (or auxiliary power) market segments. The following bulleted list summarizes the findings of the current study:

- Propane will not likely be used to any significant degree in automotive fuel cell applications of the future.
- Potential niche automotive applications are more likely with hydrogen refueling that is based propane reformation technology, which may be applicable to some remote re-fueling locations.
- The much more likely widespread application of propane fuel cell technology is in the auxiliary power unit (APU) and small stationary power markets, such as remote back-up power, uninterruptible power supplies, and residential co-generation (e.g., as in Japan).
- The advancement of flexible, high power density, low cost and efficient propane fuel processing technology is what is primarily required to facilitate the early introduction of fuel cell technology especially in the remote power and backup power sectors.

- Regulatory, safety, and policy understanding and the general acceptance of and consumer comfort with propane fuel may contribute to the general acceptance of fuel cell technology for remote power, backup power, and APU markets.

- The technical features and capabilities that a propane reformer-based fuel cell product may be able to offer (remote re-fueling, higher fuel energy density, acceptable storage standards/policies, longer back-up power supply, additional on-board power and electrical features, recreational power, etc.) might significantly advance consumer acceptance of fuel cell technology.

- Both PEMFC and solid oxide fuel cells (SOFC) will continue to require some type of fuel processor for cost effective early introduction to the marketplace. These fuel processors will likely require significant integration with the fuel cell itself, leading to the need for PERC to work closely with fuel cell manufacturers and fuel cell systems integrators in important near-term application areas.

- A significant challenge for all fuel cell fuel processing technology is the removal of sulfur, which poisons many reformer and fuel cell catalysts. Most groups are removing sulfur through an absorption or adsorption bed of either an activated carbon or zinc-oxide. These beds have proven effective, but, the capturing all of the sulfur compounds that can be present in propane is a challenge, and the logistics of bed replacement or re-generation are challenging.

- Propane can be electrochemically oxidized directly in a fuel cell system, instead of using a fuel processor. The direct electrochemical oxidation of propane in a solid oxide fuel cell is an attractive long-term option worthy of consideration and one that is currently being advanced by several organizations.

- This report for PERC has uncovered at least 20 organizations around the world that have tested fuel processing technology on propane, which is promising.

- By far the most significant challenge for propane fuel processing and fuel cell systems in general is associated with cost reduction and the ability to produce viable and reliable fuel processor-fuel cell systems at a cost that is low enough to compete in the marketplace.

- The PEMFC market foci on APU and back-up power applications, where propane use as a fuel may have some distinct advantages compared to other energy carrier solutions, are promising market foci for PERC to consider.

2.2 Leveraging of Limited PERC Funds

Current PERC funding is for individual projects that have a limited number of project partners. Recommend other arrangements and joint undertakings that the propane industry should consider being a part of, to make better use of limited funds.

2.2.1.1 Plug Power Proposal

On August 23, 2004, Spencer Management provided PERC with its assessment of a proposal from Plug Power to modify their technology for propane application. Sustained base

and intermediate load power delivery is directly proportional to the amount of on-site storage of fuel and the efficiency by which that fuel is consumed. The current fuel of choice is hydrogen due to the difficulties in PEM fuel cell technologies handling impurities naturally found in natural gas and propane. Storage of multiple cylinders of hydrogen will require them being located on the exterior of the end-user's building and the installation of expensive piping for the hydrogen from the storage to the fuel cell. Spencer Management asserted that LPG is the only candidate for reasonable storage of fuels for fuel cell technology in remote applications not served by the utility grid, but there has yet to be a successful LPG fuel cell technology demonstrated that gives promise for this option. Therefore, the firm strongly urged that in this first Phase of activity with Plug Power, the fuel supply, storage and cost strategies be investigated and reported to PERC. The firm believes that the issue has major ramifications to the overall feasibility of propane fueled fuel cells in remote application.

Plug Power represented to the SEC and its shareholders that,

> Our initial fuel cell systems currently cost significantly more than many established competing technologies. If we are unable to develop products that are competitive with competing technologies in terms of price, reliability and longevity, consumers will be unlikely to buy our products. The price of our products depends largely on material and manufacturing costs. We cannot guarantee that we will be able to lower these costs to the level where we will be able to produce a competitive product or that any product produced using lower cost materials and manufacturing processes will not suffer from a reduction in performance, reliability and longevity.

In summary, Spencer Management endorsed a Phase I funding of modifying PEM fuel cells for propane fuel applications in remote applications as long as it decoupled with the dissimilar specifications and load profiles of the telecommunication applications. It is not believed that PERC has an interest in the telecommunications market niche that has a load profile of less than 20 hrs per year.

2.2.1.2 IdaTech

On February 13, 2004 PERC sought a review of IdaTech's proposal for Proposed Project #10986 entitled "Propane Fuel Cell Development, Integration and Demonstration for RV Applications". There is no question that IdaTech in PEM fuel cells and Cummins Power Group (CPG) in the RV powergen market creates a formidable team for this application. Their knowledge of the power system requirements, demand loads, specifications and competitive costs and technologies provides PERC with a confidence that if the team is properly directed and oriented, there is a relatively small risk related to the selection of these contractors.

The guidance given twenty-two months ago remains accurate today when it was asserted that this proposal was overreaching with respect to market penetration rates and timing given the significant reductions required in the spatial, weight and cost features of a PEM/battery system in the RV market. This is not to say that propane fueled PEM fuel cell systems for the RV market is not a superior application; rather it is to assert that the resources, schedule and challenges are greater than that presented by IdaTech and CPG. Other advice was provided, but due to the business proprietary nature of the material, it is not reflected herein.

This evaluation of IdaTech/Cummins PEM fuel cell system was based upon the information contained in the proposal and publicly available information regarding IdaTech and CPG. It should be emphasized that although Spencer Management Associates serves as DOE-NETL's external consultant on appraising the Solid Oxide Fuel Cell Program, to which Cummins Power Group is one of six industrial team leaders, none of the proprietary SOFC related information was used in the review of this PEM based system.

2.2.1.3 HARC Big Bend Proposal (Docket 11128)

On February 13, 2004, PERC sought a review of HARC's proposal for an approximately 5 kWe fuel cell demonstration project at Big Bend National Park. The proposal is technology neutral between PEM and SOFC technologies, and a competitive solicitation is proposed within the $262,000 funding request. The firm found that the cost/benefit of this project to be poor due to the number of other demonstrations programs being conducted by IdaTech and Plug Power and to a lesser extent Acumetrics and Nuvera. There are also other competitive solicitations by South Coast Air Quality Management District, NYSERDA and US Department of Defense in comparably sized units and applications.

2.2.1.4 2.1.2.5 National Fuel Cell Research Center

NFCRC currently receives funding from more than 35 separate organizations (NFCRC Members). Many of these organizations support the NFCRC because of the significant leveraging of their funds that occurs by supporting projects at the NFCRC that leverage the funds provided by other organizations. Leveraged research and development projects are the regular means of doing business at the NFCRC. As a result, NFCRC is not only familiar with the process of leveraging limited research and development funding, but has expertise in arranging for leveraged funding, is experienced with establishing alliances to forge fuel cell systems development, and is currently working with a large number of entities that may be interested in teaming with PERC in future projects.

To meet the objective of PERC to significantly improve the leveraging of funds and make better use of limited PERC funds, the team has present the priority research and development portfolio developed in this task to the fuel cell community that NFCRC works with, and encouraged consideration of teaming, and will sought potential partners for PERC projects.

3 Accelerating Commercialization

3.1 Candid Assessment of Propane's Status within Fuel Cell R&D

The fuel cell market is not a robust market at this time. Rather, fuel cells are just beginning to emerge in stationary power applications, are near to emerging in portable power applications, and are in a pure research and development stage in automotive applications. Nonetheless, advances in each of these market segments are significant to the application of propane to fuel cell systems, since many of the fuel cell system technology advances can be applied across market segments.

Recent fuel cell market success includes the introduction of products for the Japanese residential co-generation market. Major companies such as Tokyo Gas with Ebara-Ballard and Shin-Nihon-Sekiyu (New Japan Petroleum) introduced commercial residential co-generation products in 2004. This market is one that could grow significantly and is also one that could be well served by the propane industry, especially in more remote areas of Japan (and other countries) where natural gas infrastructure is not present.

Many of these Japanese residential co-generation markets are well suited to using propane fuel due to remote location and/or the relative high cost of other fuel sources. Significantly, Matsushita Electric Works teamed with the Japanese Gas Association to develop and demonstrate a 1 kW propane gas reforming unit and have tested the fuel processor as integrated with a PEMFC. In addition, Osaka Gas developed an LPG reformer for a residential fuel cell system. Although LPG can contain significant levels of other hydrocarbons, Osaka Gas technology is proven on fuels containing primarily propane and is likely well suited to more pure propane use.

Fuel cell technology is poised to significantly contribute to meeting stationary power, portable power and transportation energy needs in the near future. Recent technology advances, market penetration success, and policy initiatives portend an exciting future for fuel cell technology. Although most of the recent success has neither directly involved the use of propane in fuel cells nor demonstrated propane reformation technology, the potential of fuel cell technology to impact and change as well as depend upon the propane community is significant.

Propane can be used in fuel cell systems either directly or through the use of a fuel processor. The direct electrochemical oxidation of propane in a solid oxide fuel cell is an attractive long-term option worthy of consideration and one that is currently being advanced by several organizations. In the short-term, propane use in fuel cell systems requires a propane fuel processor (for use with either a PEM or SOFC). In this case several fuel cell and fuel processor organizations have already proven the feasibility of processing propane sufficiently for use in fuel cell systems. Although this technology still needs some technical advancement, in particular focused on integration of propane fuel processors into efficient and robust complete fuel cell systems, propane reformer fuel cell systems investments should include demonstrations of the technology aimed at commercial prototypes and eventually commercial products.

Regarding propane fuel processing, the current effort has uncovered at least 20 organizations around the world that have tested fuel processing technology on propane. While these organizations have met with varying degrees of success and while some are far from proving that integration into a robust fuel cell system is feasible, this level of effort is encouraging and impressive suggesting that the use of propane in future fuel cell systems is likely.

The consensus amongst the fuel cell and fuel processing community today is that direct hydrogen fueling of fuel cell vehicles will be the ultimate solution. This strategy simplifies the automobile engine making it sustainable and cost effective to deploy and leads to the best life cycle emissions and efficiency impacts. This strategy is also consistent with the long-standing observed costs of hydrogen production, which today, is most inexpensively produced by steam reformation of natural gas in large hydrogen production facilities. So, hydrogen fueled vehicles and the concomitant H_2 infrastructure development and hydrogen storage advances are part of the long-term solution.

It is not likely that propane will be used to any significant degree in automotive fuel cell applications of the future. Potential niche automotive applications are more likely with hydrogen refueling that is based propane reformation technology, which may be applicable to some remote re-fueling locations. The much more likely widespread application of propane fuel cell technology is in the auxiliary power unit (APU) and small stationary power markets (such as that described above for the Japanese co-generation market).

The development of flexible, high power density, low cost and efficient propane fuel processing technology could facilitate the early introduction of fuel cell technology especially in the remote power and backup power sectors. This will likely be accomplished by early introduction of propane fuel cells into the back-up power, uninterruptible power supply (UPS), and APU markets. The propane option is attractive because it could address the primary challenges of hydrogen storage (low energy density, high cost, safety concerns, consumer acceptance) that are a significant hurdle for market adoption of current fuel cell applications in these markets.

Regulatory, safety, and policy understanding and the general acceptance of and consumer comfort with propane fuel may contribute to the general acceptance of fuel cell technology for remote power, backup power, and APU markets. The technical features and capabilities that a propane reformer-based fuel cell product can offer (remote re-fueling, higher fuel energy density, acceptable storage standards/policies, longer back-up power supply, additional on-board power and electrical features, power while camping, etc.) might significantly advance consumer acceptance of fuel cell technology in general.

Propane fuel processing technology could also play an early and long-term role as a more general stationary power fuel processor (especially in remote and back-up applications, and more generally in developing countries where fuel infrastructure is scarce and the need for new installed power generating capacity is greatest). The need for propane fuel processing technology could be great regardless of fuel cell type or fuel type. Both PEMFC and solid oxide fuel cells (SOFC) will continue to require some type of fuel processor for cost effective early introduction to the marketplace (until there is a significant penetration of the hydrogen economy – perhaps 50-100 years off). These fuel processors will likely require significant integration with the fuel cell itself, leading to the need for the Propane Education

& Research Council to work closely with fuel cell manufacturers and fuel cell systems integrators in important near-term application areas.

By far the most significant challenge for propane fuel processing and fuel cell systems in general is associated with cost reduction and the ability to produce viable and reliable fuel processor-fuel cell systems at a cost that is low enough to allow competition with the existing and increasingly efficient and clean competing technologies.

Fortunately, the current fuel cell market, especially that for PEMFC systems, is focused on APU and back-up power applications where propane use as a fuel may have some distinct advantages compared to other energy carrier solutions. PERC should focus its short term research and development on the advancement of propane fuel cells for residential power applications and seize upon the undeniable leadership in Japan. PERC should focus its longer-term research efforts on the direct electrochemical oxidation of propane in solid oxide fuel cell systems.

By building upon the results and R&D assessment of Task 1 and the leveraging opportunities identified in Task 2, the team provides herein the options and recommendations for a new or revised funding strategy that can accelerate propane fuel cell commercialization.

3.2 The Global Leadership by Japan in Propane Fuel Cells

One observation derived from the PERC's R&D portfolio, the RFP and the Roadmap is that there will need to be a much stronger integration of the PERC portfolio with the Japanese propane-oriented fuel cell program. The possible non-Japanese exceptions to this global leadership are Plug Power, Acumentrics and Nuvera which are discussed elsewhere herein. Recommendation of Companies with Competencies for Addressing Propane-Oriented Fuel Cell R&D Priorities on page 48 is replete with examples of global Japanese companies cost sharing with their government, e.g. Nippon Oil, that are currently rolling out a 100 unit, 1 kW propane fuel cell demonstration programs. Other companies involved in fuel cell demonstrations capable of LPG use include Ebara Ballard, Hitachi Home&Life Solutions, Ishikawajima-Harima Heavy Industries, Kurita Water Industries, Marubeni, Matushita Electrical Industrial, Mitsuhishi Heavy Industries, Sanyo Electric, Toshiba, Toyota Motor, Liquefied Petroleum Gas Center, Mitsubishi Corporation, Idemitsu Kosan Co., Ltd., Matsushita Electric Industrial Co., Ltd., Air-Water Inc. and Iwatani International Corporation. The Japanese in propane-oriented fuel cells have far more government subsidized fuel cell developers currently deploying demonstrations units to win the fiercely competitive residential market. Therefore, if PERC is knowledgeable about the Japanese successes and failures, the US commercialization schedule would become accelerated and proceed with a higher probability of sustainability.

Extracting data on a timely basis from the Japanese and structuring partnerships is always problematic, but the team drew upon its resources at the World Bank, the Japanese members in NFCRC, and our ongoing relationship with the Fuel Cell Development Information Center of Japan (FCDIC) to assist PERC in becoming more integrated with the Japanese program. Presented within this section are just two examples of the Japanese leadership, Nippon Oil and Toshiba, and the substantial balance of ongoing Japanese propane fuel cell commercialization is presented in Appendix 1.

3.2.1 Nippon Oil

Nippon Oil has developed four different catalysts for use in kerosene and propane fuel cells applications, and has one of the largest propane fuel cell demonstrations programs in the world. Over 100 units have been installed in unit sizes of 750 W (in collaboration with Sanyo), 1 kW (in collaboration with Ballard and 1-10 kW (kerosene fueled, in collaboration Mitsubishi Heavy Industries). At the 2005 Fuel Cell Seminar, Spencer Management reiterated PERC's interest in receiving one or more of the Nippon units for field testing in the US. Nippon Oil is grateful for the continued interest in all of their propane related products, but they remain undecided as to when they will be releasing their fuel cell systems for testing outside of Japan. Nippon Oil recently reported 34% AC electrical efficiency, 76% total efficiency in the CHP configuration for their 750 W propane fueled unit (Figure 4). They also reported a catalyst life of 40,000 hrs which is outstanding compared to their competitors (Figure 3). Byron Washom shared the podium at the 2005 Fuel Cell Seminar with Dr. Kazuo Koseki who is head of the Japanese Fuel Cell Development Information Center and renewed PERC's interest with him as well. Nippon Oil's US offices for fuel cell market development were consolidated back to Tokyo in September 2006.

Figure 3 Nippon Oil's Forecast for 40,000 Hours of Catalyst Life

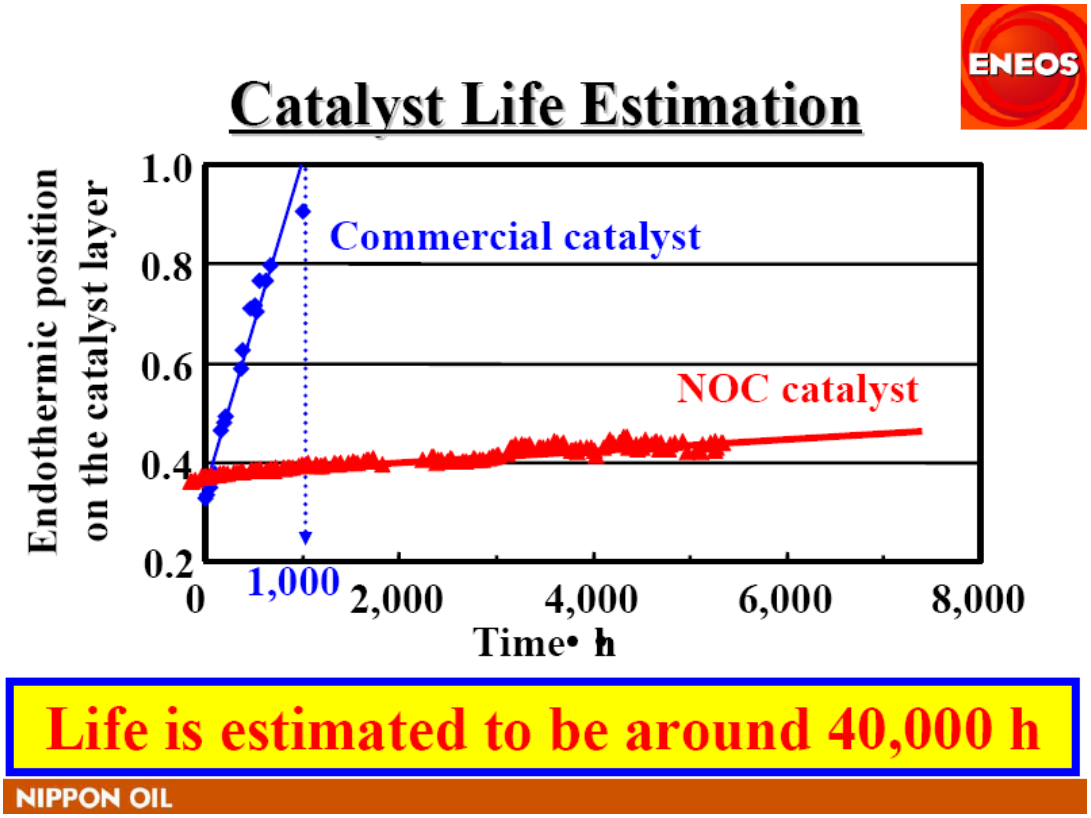


Figure 4 Nippon Oil's 750W Propane Fuel Cell System

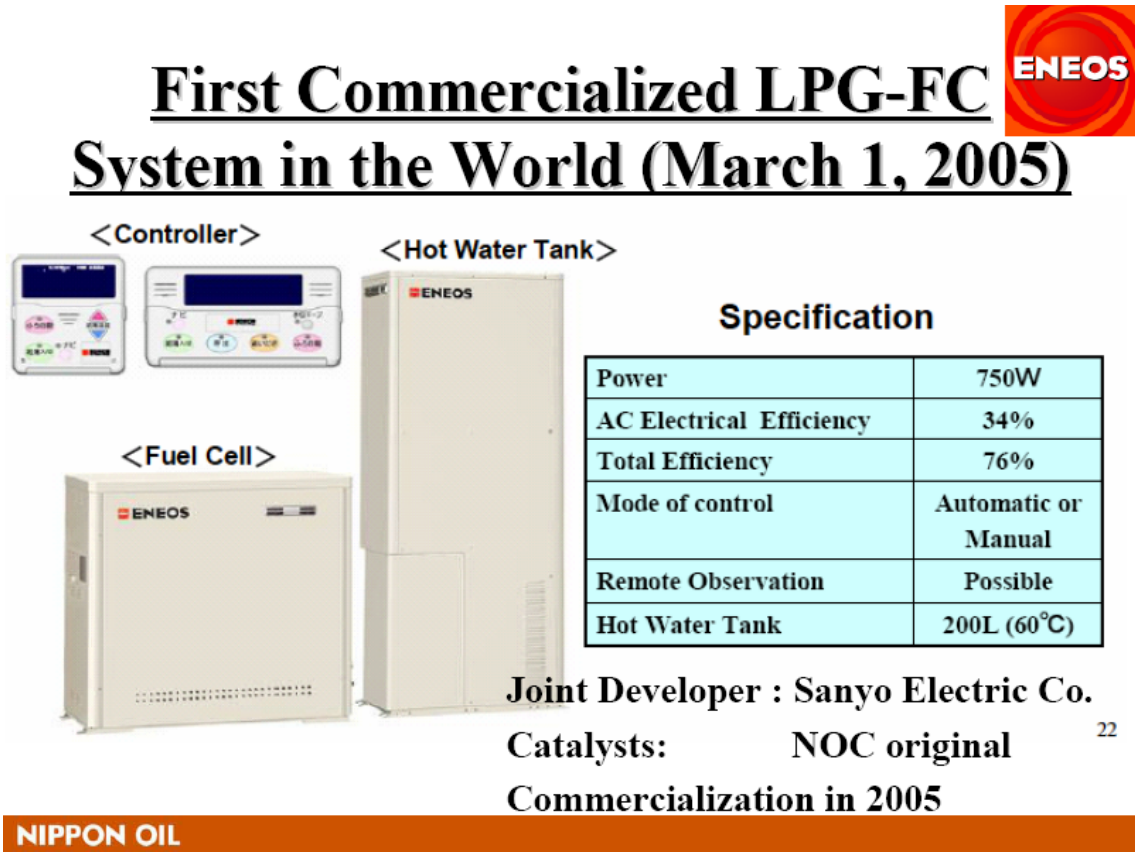


Table 1 Characteristics of the Japanese Residential Fuel Cell Market (2006)

Fuel type	LPG	Kerosene	City Gas
Principal suppliers	Nippon Oil	Nippon Oil	Tokyo Gas
Japan Energy	Osaka Gas		
Idemitsu	Toho Gas		
FC makers	Sanyo Toshiba	Ebara Ballard	Matsushita
Ebara Ballard			
Sanyo			
Price of leasing	US$ 60 M/ year	US$ 60 M/ year	US$ 100 M/ year
Estimated Sales Units (2006)	611 Units	75 Units	491 Units

Data supplied by Nippon Oil in August 2006 indicated that US$60M/year of propane fuel cell leasing is current ongoing or planned in Japan with propane fuel. This represents 23% of the Japan national total of US$260M/year. Kerosene fueled systems represents another US$60M, or 23%, and City Gas represents US$100M/year, or 54%. There are total of 611 LPG units under lease contract, 75 kerosene units under lease contract and 491 city gas

units under lease contract. As indicated in Table 1, all of the leased units for LPG and Kerosene are with Nippon Oil as the principal supplier, and Tokyo Gas is the principal supplier for the city gas units.

3.2.2 Toshiba

Toshiba International continues to make strong progress towards their PEM city gas/LPG fuel cell for the Japanese market as well. At both the 2004 and 2005 Fuel Cell Seminar, Toshiba reported AC electrical efficiencies of greater than 37% (LHV) and total efficiencies of 77% for their 700 W residential units. Toshiba International has been developing resident PEM systems since FY2000. More than 50 units have been demonstrated, cell stack durability and stability of more than 9000 hours in full stack has been achieved, and decay rates of 2mV/1000 hr has been published by Toshiba. Toshiba reported in 2004 that, the PEM system is, "superior to Gas Engine based CHP systems for power efficiency and operational flexibility, but it consumes some energy for start-up and idling. Therefore, it is recommended to operate 24 hours continuously with the load following mode to maximize energy savings." Large scale field testing of 100 residential units in 2005-06 is planned. One field unit was operated for 4200 hours without any unscheduled maintenance.

3.3 US Fuel Cell Development and Market

The commercial stationary power fuel cell market was also significantly advanced in 2005. This advancement was due primarily to the significant sales of FuelCell Energy's Direct FuelCell® products. In 2004, FuelCell Energy (FCE) had 42 systems either sold or installed. These installations primarily comprise the 250 kW DFC 300® carbonate fuel cell product of FCE and include applications in wastewater treatment, commercial, industrial, mission critical, hotel, university, and utility grid support applications. Significantly, the installation and operation of the world's largest fuel cell is being demonstrated by FCE in a 1.0 MW facility operating on digester gas in King County, Washington. A separate 2 MW FCE fuel cell was successfully tested on coal synthesis gas in Terre Haute Indiana in 2004. These accomplishments indicate the fuel flexibility of FuelCell Energy technology. However, FuelCell Energy technology has only been tested on the bench scale with propane because the size of their current commercial products (>250kW) is not well suited to the propane market.

In the automotive sector there were many significant advancements, and these are significant to PERC primarily because the proton exchange membrane fuel cell (PEMFC) technology of the automotive sector is likely to be very similar to that used in propane PEMFC systems. One major transportation market success was that of the Clean Urban Transport for Europe (CUTE) project of the European Union. Thirty-three (33) fuel cell buses in all are being tested in nine European cities covering a distance of over 40,000 km in 2004. Other advancements have appeared in fuel cell concept cars manufactured by nearly every major automobile manufacturer in 2004. The significant technical advance of successful cold-weather start-up and operation of PEM fuel cells in freezing conditions was announced by several automobile companies in 2004.

3.3.1 U.S. Department of Energy Programs

The President of the U.S. together with the U.S. Department of Energy (DOE) and its subcontractors has launched us into the era of fuel cells and the hydrogen economy. The

logic of a hydrogen economy is compelling and the recent advances of fuel cell technology are promising. The U.S. government supports these developments because, if successful, they can help the U.S. meet several strategic goals: (1) use domestic resources – solar, wind, hydro, and coal – for energy demands, (2) reduce dependence on imports of foreign petroleum, (3) reduce green house gas (and other) emissions, and (4) potentially enhance electricity system security and reliability.

The U.S. government has several major initiatives that should advance solid oxide fuel cells (SOFC). In addition, DOE is supporting the advancement of proton exchange membrane fuel cells (PEMFC) and hydrogen production, storage, and delivery/dispensing technologies. Clear Skies and Climate Change programs aim to reduce CO_2, NOx, and SO_2 emissions. Fuel cells have no emissions so this technology figures significantly in these DOE strategies. In addition, the introductory consideration of distributed generation technologies – gas turbines, internal combustion engines, SOFC, PEMFC, reforming, energy storage – bodes well for the widespread use of many of the fuel cell and hydrogen technologies that are being advanced by DOE. The use of fuel cells is expected to bring about the hydrogen economy. However, commercialization of fuel cells is expected to proceed first through portable (including generator power) and stationary applications (including back-up power).

3.3.1.1 Office of Fossil Energy (FE)

There are two major DOE programs that support fuel cell systems advancement in the Office of Fossil Energy. The two programs are the FutureGen and Solid State Energy Conversion Alliance (SECA) programs.

All aspects of the DOE Fossil Energy R&D Program now support the FutureGen Program and Project – including Distributed Generation (DG) fuel cells. DG is developing scaled-up fuel cell and hybrid $400/kW power blocks for FutureGen and other advanced coal based power systems. DG Systems are critical to achieving cost, efficiency and emissions targets. SOFC has tremendous cost reduction potential based on mass customization - mass production of common modules for multiple applications. Low-cost, $400/kW SECA fuel cell hybrid is key to achieving 60% higher heating value (HHV) efficiency, low-cost, $850/kilowatt (kW) advanced coal based power systems.

Fuel cells and fuel cell hybrids have ultra low emissions, produce water, and can be configured to isolate/segregate CO_2 - all features useable in FutureGen and advanced coal based systems. SECA fuel cells and hybrids can operate on syngas and hydrogen in FutureGen systems as well as other conventional fuel.

The most significant program that is supporting the advancement of fuel cell technology in the Office of Fossil Energy is the Solid State Energy Conversion Alliance (SECA). The SECA alliance includes 6 Industrial Teams and a host of research and development organizations that advance SOFC technology through a Core Technology Program that is part of SECA. The Core Technology Program is developing science and technologies that resolve specific technical challenges and barriers faced by the SECA Industrial Teams in meeting the DOE goals for the SECA program.

The DOE goal for SECA Industrial Teams is to develop a 3 - 10 kW solid-oxide fuel cell system including stack and balance of plant that has a factory cost of $400/kW by 2010. The goal is to develop solid-oxide fuel cell power systems that have broad applicability via use of mass customization techniques. Development of solid-oxide fuel cell power systems that are

applicable to stationary, mobile, and military applications with minimal differences in core module components is desired. DOE considers the development of "high power density" (e.g., > nominal 400 ma/cm2 at 0.7 volts per cell) solid-oxide fuel cells an important component of meeting the 2010 cost goal. A goal of DOE is to encourage the entry of one or more fuel cell systems developed in the SECA program into one or more commercial markets at the earliest possible date.

The National Energy Technology Laboratory (NETL) and Pacific Northwest National Laboratories (PNNL), in partnership with private industries, are leading the SECA Program. If highly efficient, ultra-clean fuel cell technology can move from niche markets to widespread use in stationary power applications, the result will be significant national benefits.

Potential SECA applications include commercial trucks, military vehicles, aircraft, and ships are all. To lower the cost of fuel cells as much as possible it is important to put fuel cells in all of these applications. A number of other government agencies and offices, federal and state are directly supporting work that helps SECA. DOE views this combined effort representing the spectrum of applications as essential to a successful SECA program.

Overall, SECA is an $800 million program through 2010 with $375 million from DOE for the industry teams. SECA has six industry teams working on designs that can be mass-produced at costs that are ten-fold less than current costs. Many alternatives are being pursued.

The SECA industry teams have surpassed the interim goal of 60 percent fuel utilization for their short stacks during the first quarter of FY 2004. The Industrial Team/Core Technology funding split has been 60/40. Technology progress is constantly monitored and priorities adjusted as needed. The first priorities, gas seals and metal interconnects, are critical to stack operation. The industry team R&D needs also include lower temperature components, higher power density, insulation, fuel reforming, and power electronics. Progress of each of the Industrial Teams is described in more detail below.

Delphi

Delphi is close to meeting its Phase 1 fuel cell system performance targets. Its 3rd generation design has achieved 420mW/cm^2 in a 30-cell (2 stacks). Delphi, in partnership with Battelle/PNNL, the world's leading SOFC laboratory, is developing a 5 kW, planar, 700C - 800C, anode-supported SOFC compact unit for the distributed generation and auxiliary power unit markets. Delphi is expert at system integration and high-volume manufacturing and cost reduction. They are focused on making a very compact and light-weight system suitable for auxiliary power in transportation applications. Delphi and Battelle will demonstrate a 5-kilowatt system that operates on common fuels of natural gas and diesel with an eventual interest in pursuing military logistical fuels. The University of Utah is participating as a consultant to the team. The original DOE contract to this team provides $74.6 million while Delphi and its partners will contribute $60.9 million.

Additional public information on the Delphi SECA contract and design initiatives can be found at:
http://www.netl.doe.gov/publications/proceedings/02/SECA/SECA3Botti.pdf

http://www.netl.doe.gov/publications/proceedings/03/seca/James%20Zizelman.pdf

http://www.netl.doe.gov/publications/proceedings/04/seca-wrkshp/Delphi%20-%20Shaffer.pdf

General Electric

General Electric (formerly Honeywell, Torrance, CA) is designing, developing and demonstrating a modular, 3- 10-kilowatt solid oxide fuel cell system for a wide range of power-generation needs in their SECA effort. The self-contained prototype will be able to operate on a variety of fuels, including propane, and can be designed as a stand-alone power plant tailored for a specific market, or integrated into a larger system. The original DOE contract will provide nearly $74 million for the 10-year project with GE contributing $59 million.

GE is initially developing a natural gas 5 kW, planar, 700C - 800C, anode-supported SOFC compact unit for residential power markets. GE is evaluating several stack designs and is especially interested in extending planar SOFC's to large hybrid systems. GE is already very close to achieving its Phase I SECA targets for stack power density and utilization. Using a planar square SOFC stack, GE has achieved record 238 milliwatt (mW)/ square centimeter (cm^2) @ 93% fuel utilization (U_f) and stable operation at 95% U_f.

Additional public information on the General Electric's SECA contract and design initiatives can be found at:
http://www.netl.doe.gov/publications/proceedings/02/SECA/SECA3Minh.pdf

http://www.netl.doe.gov/publications/proceedings/03/seca/Nguyen%20Minh.pdf

http://www.netl.doe.gov/publications/proceedings/04/seca-wrkshp/GE%20Energy%20-%20Minh.pdf

Siemens Westinghouse Power Corp.

Siemens Westinghouse Power Corporation (SWPC) is developing 5-10 kW products to satisfy multiple markets. SWPC has developed a new tube design for their 5 kW units that use flat, high power density (HPD) tubes. This allows for a shorter tube length and twice the power output compared to their current cylindrical tube. Siemens Westinghouse's HPD flattened tubes have achieved a respectable 262 mW/cm^2 @ 85% U_f at 1000C.

SWPC plans to develop a 7- to 10-kilowatt solid oxide combined heat and power system for residential applications, and a 3-to 10-kilowatt auxiliary power unit for automotive applications with military logistical fuels. Working with Siemens are Fuel Cell Technologies, Blasch Precision Ceramics, Georgia Institute of Technology, Lennox Industries, the Trane Company, Dominion Resources, Ford Motor Company, Eaton Corporation and Newport News. The original DOE contract will provide $47.8 million while Siemens Westinghouse and its team will provide $32.8 million.

Additional public information on the SWPC SECA contract and design initiatives can be found at
http://www.netl.doe.gov/publications/proceedings/02/SECA/SECA3George.pdf

http://www.netl.doe.gov/publications/proceedings/03/seca/SD%20Vora.pdf

http://www.netl.doe.gov/publications/proceedings/04/seca-wrkshp/Siemens%20Westinghouse%20-%20Vora.pdf

Cummins Power Generation and McDermott Technology

Cummins and SOFCo EFS are developing a 10 kW product initially for recreational vehicles that would run on propane using a catalytic partial oxidation reformer. This effort is especially relevant to PERC. The team has produced a conceptual design for a multilayer SOFC stack assembled from low-cost "building blocks." The basic cell, a thin electrolyte layer (50-75 micron), is fabricated by tape casting. Anode ink is screen-printed onto one side of the electrolyte tape, and cathode ink onto the other. The printed cell is sandwiched between layers of dense ceramic that will accommodate reactant gas flow and electrical conduction. The assembly is then co-fired to form a single repeat unit.

The Cummins team is pursuing stationary and mobile markets by producing and testing a modular, 10-kilowatt system that is quiet, highly reliable, highly efficient, and emits virtually no pollutants. The unit will be designed to compete with and possibly replace current reciprocating engines of the same size. The project accelerates McDermott's existing solid oxide fuel cell program, and makes use of Cummins Power Generation's skill in integrating systems and penetrating a variety of small-size consumer and commercial markets. Key subcontractors are Ceramatec, Inc. and Advanced Refractory Technologies, Inc. The original DOC contract contributes $74.2 million while the Cummins/McDermott team will provide $91.5 million.

Additional public information on the Cummins SECA contract and design initiatives can be found at:
http://www.netl.doe.gov/publications/proceedings/02/SECA/SECA3Norrick.pdf

http://www.netl.doe.gov/publications/proceedings/03/seca/Daniel%20Norrick.pdf

http://www.netl.doe.gov/publications/proceedings/04/seca-wrkshp/Cummins%20-%20Norrick.pdf

FuelCell Energy Corporation Technology

FuelCell Energy Inc. (FCE) will bring its long history of fuel cell development to its teaming relationship with Gas Technology Institute (GTI) and VERSA Power. Versa Power is a relatively new company, established in Colorado, to commercialize solid oxide fuel cell technology that may emerge from this Industrial Team. In addition, through acquiring Global Thermal Electric, which has a 5MW/year manufacturing facility and over 25,000 hours of testing experience on their RP-2, 2kW units. The FCE SECA program is about 2 years younger than those of the above-mentioned SECA Industrial Teams, so current technical progress is a bit behind those listed above. Additional public information on the FCE SECA contract can be found at:

http://www.netl.doe.gov/publications/proceedings/04/seca-wrkshp/Fuel%20Cell%20Energy%20-%20Patel.pdf

Acumentrics Corporation Technology

Acumentrics uses a micro-tubular design and is already offering early units for field testing with propane fuel and natural gas. It is interested in the IT and UPS market. It has conducted over a dozen early unit field tests. The advantages of smaller diameter Acumentrics tubes are higher volumetric power density and rapid start-up (less susceptible to thermal shock). They have already achieved 63 thermal cycles. Additional public information on the Acumentrics SECA contract and design initiatives can be found at:

http://www.netl.doe.gov/publications/proceedings/04/seca-wrkshp/Acumentrics%20-%20Bessette.pdf

3.3.1.2 Office of Energy Efficiency and Renewable Energy (EERE)

The President's Hydrogen Fuel Initiative commits government funding for accelerated research, development, and demonstration programs that will enable an industry commercialization decision on hydrogen fuel and fuel cells by 2015. At the present time, there are three primary technology barriers that must be overcome for the wide-spread deployment of hydrogen fuel cell vehicles:

1) The cost of safe and efficient hydrogen production and delivery must be lowered to be competitive with gasoline without adverse environmental impacts.
2) Fuel cell system costs must be lowered to $30 per kilowatt while meeting performance and durability requirements.
3) On-board hydrogen storage systems must be developed that allow a vehicle range of greater than 300 miles while meeting packaging, cost, and performance requirements.

Hydrogen is a promising energy carrier because it can be derived from diverse domestic resources and also has potential for environmental benefits. The DOE Hydrogen Program is funding high risk R&D to accelerate the introduction of economically competitive hydrogen into the transportation fuel market. Although propane will not likely be widely used in the transportation market, these DOE programs are of significance to PERC since the basic fuel cell and fuel processing technology that is advanced in these EERE programs will likely be similar to that used in propane fueled fuel cell systems.

The major accomplishments in the DOE EERE hydrogen production and delivery activities that are related to PERC interests include the following [Reid et al., 2004]:

- Completed research and design that is estimated to achieve the DOE 2005 cost target of $3.00/kg H_2 at the dispenser for distributed production of hydrogen from natural gas (assumptions: 690 kg hydrogen/day, 11% capital recovery factor, greater than 100 units annually, $4/MMBTU HHV natural gas, and 90% utilization).
- Developed a pressure swing adsorption (PSA) system, delivering 99.999% pure hydrogen from a steam methane reformer that achieved a 2 to 4 times cost reduction compared with commercially available units. The PSA has a smaller

footprint and exceeds the DOE 2005 energy efficiency target of 82% (LHV) for purification.

- Demonstrated hydride-based compression and purification that is anticipated to have reliability and durability advantages over mechanical compression and conventional purification technologies.
- Demonstrated an improved reforming catalyst reducing attrition and coking for use in biomass pyrolysis processes.

In 2004, an analysis project was initiated to calculate a levelized hydrogen cost with a documented consistent set of assumptions. The goal is to bring consistency and transparency to hydrogen cost analysis. With help from national labs and industry, the project has completed base cases with sensitivity analysis for current, mid-term, and long-term production/delivery scenarios: natural gas reforming, coal, biomass, nuclear, central station wind / electrolysis, distributed electrolysis, and liquefied and compressed hydrogen delivery.

A hydrogen production and delivery solicitation was held in FY-04 with the following ten topic areas: Hydrogen from biomass; Photolytic processes; Distributed production technologies; Hydrogen separation and purification technologies; Advanced electrolysis systems; Solar high temperature thermochemical water splitting cycles; Hydrogen production infrastructure analysis; Hydrogen delivery scenarios; Crosscutting projects; and University projects. Projects selected and awarded will move the hydrogen production and delivery technologies toward goals needed to enable an industry commercialization decision by 2015 and the long-term goal of a hydrogen-based economy.

The FreedomCAR and Fuel Partnership include 5 major energy companies: BP, ChevronTexaco, ConocoPhillips, ExxonMobil, and Shell. Technical Teams have been established to understand the technical challenges in key areas and to identify the most promising technologies to overcome the barriers. Three Technical Teams are focused on hydrogen production and delivery issues: the Hydrogen Production Tech Team, the Hydrogen Delivery Tech Team, and the Fuel Pathway Integration Tech Team. Each team is composed of representatives from each of the industry partners, DOE, and national laboratories.

The Hydrogen Production Tech Team's role includes data/technology gap identification and analysis of R&D performance goals, targets, and milestones. The team's current focus is the development of an industry/government technology plan that identifies key research challenges for near-term technologies such as distributed reforming and electrolysis, as well as longer-term Read et al. pathways such as biomass, photolytic, and high temperature thermochemical processes. The focus is on technologies to enable a cost of $1.50/gge for hydrogen from distributed reforming of natural gas and $2.85/gge cost of hydrogen by electrolysis.

The scope of the Hydrogen Delivery Tech Team includes distribution methods for central hydrogen production. The Team will consider three hydrogen delivery pathways: gaseous hydrogen, liquid hydrogen, and novel solid or liquid hydrogen carriers. Key technology components include gaseous and liquid trucks and storage tanks; pipelines; liquefiers; terminals; compression; geologic storage; carrier regeneration; hydrogen separation/purification; dispensers; and other forecourt needs. The Team is currently

developing a plan that will identify key technical hurdles, major cost factors and performance targets.

The Fuel Pathway Integration Tech Team evaluates interfaces between various hydrogen fuel production and delivery technologies to identify analysis gaps that may represent barriers to successful energy transportation system integration. In the past year, the Team has identified groups conducting analyses relevant to fuel systems and began compiling a database of hydrogen economic studies.

3.4 Competing technologies

3.4.1 Current and Emerging Competing Technologies

In order for fuel cells and fuel processing technology to have a significant market penetration they must demonstrate market advantages. Fuel processor and fuel cell technologies must compete with current technologies that fill market needs to particularly demonstrate a cost advantage. This cost advantage may result from environmental or other regulatory policies and/or incentives, but, a cost advantage must be demonstrated nonetheless, to compete in the same mass market.

In any case, it is likely that a whole host of different technologies will succeed in these markets, with various reasons leading to consumer choice and preference. Increased market share of fuel processor – fuel cell technology could be achieved subsequent to cost competitiveness (or near competitiveness) by the introduction of enhanced user features or benefits such as better ergonomics, handling, environmental sensitivity, efficiency, mileage, electrical system enhancements, additional technical gadgetry, etc.

There are several current and emerging technologies in each of the market sectors identified and described above that are seeking to meet market needs and garner additional market share through enhanced features. The current technologies are evolving and others are emerging to pose significant competitive challenges to the introduction of fuel processing and fuel cell technology into these market sectors. As a result, there will likely be a mix of technologies adopted in each of the market sectors including some existing, some emerging technologies based upon evolution of existing technologies, and some revolutionary technologies such as the fuel processor-fuel cell engine.

In the stationary power sector competing technologies include: (1) diesel (primarily back-up) generators, (2) natural gas, diesel and propane gen-sets, (3) micro-turbine generators, (4) natural gas or propane – fired ICEs, (5) photovoltaics, (6) wind generators, (6) natural gas fired fuel cells, (8) propane or diesel fired fuel cells, and (9) hydrogen powered fuel cells. Table 4 presents the current and/or expected costs of several of these technologies as applied to stationary power generation and co-generation applications. The increased efficiency of fuel processor-fuel cell systems and their projected costs clearly make them competitive in the stationary, distributed power sector.

Table 4 Initial Costs and Features of Competing Stationary Power Technologies

Technology	Status	Capacity (kW)	Cost ($/kW)		Electrical Efficiency	Overall Thermal Efficiency
			Current	Mature		
Reciprocating Engines	Widely Used Commercial	20–20,000	400–1400	400–1400	28–35%	80%
Combustion Turbines	Widely Used Commercial	500–150,000	600–900	600–900	21–40%	80%
Photo-voltaics	Commercial	NA	3500–6000	3500–6000	NA	NA
Micro-Turbines	Commercial	30–300	600-1500	400-600	20–28%	75%
Fuel Processor - Fuel Cell	Commercial	5–3000	3500-5500*	400-1200	36-55%	85%
Hybrid FC-GT	2005-2010	250–20000	4500-6500	900-1100	60–70%	85%

*Commercial fuel cell systems including UTC Fuel Cell's PAFC and FuelCell Energy's MCFC

In the auxiliary power unit (APU) sector competing technologies include: (1) battery/alternator systems, (2) "Pony-Pack" diesel generators, (3) engine idle, (4) gas turbine (aircraft applications), (5) fuel cell (powered by various fuels depending upon the application), and (6) propane IC engine APUs. The cost of currently available APUs in the automotive sector ranges between approximately $1000/kW for luxury vehicles and $200/kW for typical passenger vehicles (Pacific Northwest National Laboratories, Solid State Energy Conversion Alliance Meeting, Washington, DC, March 21, 2002). The typical size of these APUs continues to increase with the increased customer demands for electrical and electronics-based features of automobiles. An advanced passenger automobile design (including features such as electric suspension, heated windows, fuel injectors, ABS, electric valve control, electric cooling pumps, etc.) could require a system as large as 20kW.

The typical diesel generator APU that can be purchased for long-haul trucks, as represented by the 1.3kW Pony Pack system, is available for about $3,000/kW installed (Center for Transportation Research, "Analysis of Technology Options to reduce the Fuel Consumption of Idling Trucks," Argonne National Laboratory, Contract W-31-109-Eng-38, June, 2000). APU applications in aerospace applications are required for both the provision of pneumatic and electrical resources on aircraft. Aircraft APU systems vary widely in their costs and range from approximately $3,000/kW up to $10,000/kW. Although these cost targets are attractive for fuel cells to compete, the size and weight constraints as well as the safety aspects that must be engineered in to these systems make them especially challenging applications for fuel processor – fuel cell systems.

Nonetheless, APU applications in several market sectors appear to be very attractive for fuel processor-fuel cell systems due to the high cost of competing technologies and the potential for fuel cell systems to provide enhanced features (e.g., efficiency, power, emissions reduction).

4 Fuel Processor Technology

Task 4. Ascertain whether direct fuel technology (no reformer) is a realistic option for propane and determine if PERC funding is needed to advance this technology in a way that would benefit the propane industry.

In retrospect, the statement of work was too narrowly defined with respect to the reformer issues; therefore, Spencer Management and NFCRC submits, within its fixed price contract, an additional narrative of the major reformer issues, both generically and specific to propane. The report responds in Section 4.1 to the immediate question of the feasibility of direct fuel technology (no reformer). Over and above the SOW, Spencer Management and NFCRC provide in Section 4.2 a detailed narrative of the emerging state of the art in reformer technology with a particular reference to propane. Additionally, the authors provide a tutorial on the generic reformer technologies and issues in Appendix 2.

As noted in the proposal, there was a possibility that Dr. Michael Krumpelt of Argonne National Laboratory would not be available for this task, and that in fact became the case. Dr. Jack Brouwer and Byron Washom instead addressed the relative likelihood that a reformer free fuel cell technology is not a realistic option for PERC funding consideration in PEMs.

Most notably, FuelCell Energy's molten carbonate fuel cell system is internal reforming but not applicable to small scale systems. Solid oxide fuel cells can be designed to internally reform by adding steam to the fuel or by recycling system exhaust gas. Some of the contractors in the SECA program are pursuing this approach. The team firmly believes that "direct " fuel cells are not an option for the PEMFC technology. Thus, Task 4 determined that "direct" fuel cell technologies are not a viable option for propane feedstock in the foreseeable future. This section of the report presents a brief description of fuel processor technology including some technical assessments and reporting on the state-of-the-art and recent developments in fuel processing technology, especially as they relate to the propane interests of PERC.

4.1 Recent Advancements in Direct Hydrocarbon Oxidation in Fuel Cells

In this section of the report, the major recent technical advances in the state-of-the-art of direct hydrocarbon oxidation fuel cell technology from the major companies and other development organizations are provided. Results are presented in alphabetical order of organization name.

4.1.1 Franklin Fuel Cells

Franklin Fuel Cells is one of the most well-known companies that is advancing direct hydrocarbon oxidation solid oxide fuel cell technology. The term "direct oxidation" denotes the operation of a solid oxide fuel cell by feeding a hydrocarbon fuel directly into the anode compartment of the cell without the addition of an oxidant. This ability to use "dry" hydrocarbons in a SOFC system without a separate reformation step has clear benefits in terms of system efficiency and simpler, less costly, balance of plant designs. Unfortunately, the conventional SOFC, having an anode comprised of Ni and YSZ, cannot be used for direct

oxidation as nickel is well known for its propensity to promote carbon deposition in the presence of hydrocarbons. A different anode composition is, therefore, necessary for direct oxidation.

SOFC button cells made with anodes comprising copper and ceria, instead of nickel, in a YSZ matrix have been shown by researchers at the University of Pennsylvania, and elsewhere, to be able to operate directly on dry hydrocarbon fuels delivering stable performance at power densities approaching that of state-of-the-art nickel cells. In fact, the copper/ceria/YSZ cell design developed at Penn has been licensed by a new company, Franklin Fuel Cells (FFC), and scaled up successfully to fabricate cells as large as 100cm^2. In the past two years, FFC has fabricated hundreds of large cells and demonstrated direct oxidation in single cell and multi-cell "stack" tests.

While still in the early phases of product development, FFC intends to develop direct oxidation SOFC (DO-SOFC) systems capable of operating on readily available fuels such as diesel, gasoline and natural gas. In order to quantify the benefits of FFC's direct oxidation SOFC, FFC commissioned a detailed third-party assessment of the system-level impact of FFC's SOFC technology. This study, performed by TIAX, LLC, estimates the system characteristics of FFC's direct oxidation SOFC systems and compares them to the alternatives in the 3-10 kW power range.

The alternatives considered include power systems based on Ni-SOFC, PEMFC and internal combustion engines. System efficiency, volumetric power density, and system cost estimated for high-volume production are among the attributes considered. The analysis showed that, relative to the alternatives, FFC systems could have significant efficiency advantage and be cost-competitive once the power density targets are met. [Paz et al., 2004]

4.1.2 Korea Institute of Energy Research (KIER)

KIER has developed an anode-supported micro tubular SOFC to increase the cell power density and thermal stability by decreasing the diameter of the tube compared to previous designs. This type of cell is amenable to the direct hydrocarbon oxidation approach that should be of interest to PERC. The smaller tube diameter of the current KIER design was also found to help with rapid start-up of the micro tubular SOFC. A small SOFC system made up of these types of fuel cells was successfully tested running on internally reformed butane fuel at KIER. The cell reached the operating temperature and powered a small load (propeller) in only 20 seconds. During operation, the output current of micro tube SOFC was on average 0.4A at 0.2V.

Also, the SOFC is enabling internal reformation of fuel gases such as natural gas and other hydrocarbons. Recently, KIER SOFC systems are being studied to run on a wide variety of fuels, including propane and butane. Also, since this type of SOFC can be heated up to operating temperature within a short period of time (less than 1 minute), it could be considered for portable power unit, residential co-generation, and automotive APU applications. [Song et al., 2004]

4.1.3 Mitsubishi Materials Corporation

SOFCs jointly developed by Mitsubishi Materials Corporation and The Kansai Electric Power Co., Inc. can be operated on commercial town gas, natural gas, and other hydrocarbon

fuels. Intermediate-temperature (IT) operation between 600 and 800C could provide a sufficient conditions to enable not only the internal reforming but also the use of low-cost component materials. Power generation characteristics of a single cell stack for methane and town gas with steam reforming was measured using a simplified experimental apparatus. Town gas was reformed without carbon deposition to produce the gas mixture, composition which agreed well with equilibrium conditions. The cells composed of LSGMC electrolyte, Ni-SDC anode and SSC cathode showed good performance using the reformate gas. Electrical conversion efficiency over 50 % with fuel utilization of 70 % was achieved. Longer-term tests demonstrated fuel cell stability over one thousand hours after an initial decay in performance. [Chitose et al., 2004]

4.1.4 Direct Electrochemical Oxidation of Propane

One of the other manners in which fuel cell systems can utilize propane is by direct electrochemical oxidation of propane. Direct electrochemical oxidation of propane is in an early stage of research and development than is the use of propane fuel processors followed by electrochemical oxidation of a hydrogen rich reformate stream. As a result, fewer organizations are investigating direct propane electrochemical oxidation and this technology is definitely more rare than propane fuel processing. Table 5 presents a non-comprehensive list of organizations that are investigating and/or conducting research in the area of direct hydrocarbon electrochemical oxidation in solid oxide fuel cells.

Table 5. Organizations involved in the advancement of fuel cells that can directly oxidize propane or other hydrocarbons (not a comprehensive list).

Organization	Location	Key achievement(s)
Argonne National Laboratory	Illinois, USA	Fuel processing, internal reforming SOFC
Energy Research Center of the Netherlands (ECN)	Netherlands	SOFC internal reformation
FuelCell Energy, Inc.	Connecticut, USA	Internal reformation in MCFC, SOFC
Franklin Fuel Cell Company	Pennsylvania, USA	Direct hydrocarbon oxidation in SOFC
GE Global Research	California, USA	Fuel processing, SOFC internal reformation
Mitsubishi Materials Corporation	Ibaraki, JAPAN	SOFC, fuel processing
National Fuel Cell Research Center, UC Irvine	California, USA	SOFC materials, internal reformation
Northwestern University	Illinois, USA	SOFC materials, internal reformation, on-cell electrochemical HC oxidation
Pacific Northwest National Laboratory	Washington, USA	Compact fuel processing, internal reforming in SOFC
University of Pennsylvania	Pennsylvania, USA	Direct hydrocarbon oxidation in SOFC

4.2 Fuel Cell and Fuel Processor State-of-the-Art

4.2.1 Fuel Processor and Fuel Cell System Performance Metrics

Since a PEMFC responds quite quickly to dynamic load demands, the response of a fuel cell system is often dictated by the fuel processor. Various fuel processing technologies have been significantly advanced in recent years. Perhaps the most significant advancements that are applicable to propane applications are those associated with ATR systems and various hydrogen purification strategies required for integration with PEM fuel cells. Regardless of the technology selection, however, the target performance objectives of the fuel processor system are needed. This section presents a set of draft fuel processor performance metrics that can be used to assess whether or not a fuel processing system is indeed a state-of-the-art system.

State-of-the-art performance metrics for propane fuel cell fuel processor systems are presented in Table 6 for both grid independent (not connected) and grid parallel (connected) propane fuel cell systems. These performance metrics have been developed based upon the experience of the authors and the study of current fuel processing literature data. Of the five teams involved in the DOE SECA program, GE has successfully completed its on-site Phase I testing to meet the below stated power density, start up time, transient and steady state operations that are presented below. GE will be shipping in the 3rd quarter of 2006, their Phase I unit to NETL for independent testing. The other five contractors are approximately within 3-6 months of the GE schedule.

Table 6. Draft performance metrics for a state-of-the-art stationary fuel cell propane fuel processor system.

Performance Metric	Grid Independent Target Value	Grid Parallel Target Value
Cost ($/kW)	750	500
% Efficiency (LHV)[1]	81	85
Power Density (W/liter)	10	10
Startup Time @20°C (Minutes)	45 [3]	2 hours
Transient, 10%-100% Load (Seconds)	15 [3]	NA
Steady State/Transient CO in FP Outlet (ppm)[2]	< 10 / < 100	< 10 / < 100
H_2S in FP Outlet (ppm)	< 1	< 1
Ammonia in FP Outlet (ppm)	< 10	< 10

[1] defined as ({LHV H_2 in FP Outlet} – {LHV Unutilized H_2 in FC Anode Outlet}) / {LHV Fuel In}.
This definition serves to penalize an approach that does not recapture heating value from the anode exhaust gas.

[2] only an issue for use with a proton exchange membrane fuel cell.

[3] metric comes from automotive goal - strongly depends upon the energy storage capacity of system

4.2.2 Recent Fuel Processor Advancements

Appendix 4 and Appendix 5 provides further technical information and discussions on recent fuel cell processor advancements

4.2.2.1 United States Patent Applications

Recent patent applications provide further insight into fuel processing technology developments. It is important to note that because a company has filed a patent on a concept does not mean that company is pursuing that concept. Recent patent applications related to fuel processing include:

- Pyrolysis and Pre-reforming
  - #20020041986, 4/11/02. Pyrolysis-based fuel processor. Carbon residue left on heat exchanger surface is steam reformed to generate more H2 in a cyclic process.
  - #20020031690, 3/14/2002. Cracking unit upstream of reformer makes lower hydrocarbons from higher hydrocarbons (Toyota).
- Sulfur Cleanup
  - #20020043154, 4/18/02. Zeolite for sulfur removal (Engelhard).
  - #20020041842, 4/11/02. Monolithic H2S trap; zinc oxide (ZnO) blended w/ one or more of the following metals or oxides: copper, nickel, iron, manganese (Engelhard).
  - #20020041842, 9/13/01. Two-step liquid fuel sulfur removal: 1) Mild hydrotreating; 2) Extraction to achieve <5ppm sulfur. Operates @ 300-500F, 50-500psig, 0.5-10hr^{-1} space velocity (Chevron).
- Reforming and Water Gas Shift (WGS) Catalysts
  - #20020013221, 1/31/02. WGS catalysts made of mono- and bimetallic transition metal carbides, nitrides and borides, and their oxygen containing analogs.
  - #20010026782, 10/4/01. Palladium on zinc oxide catalyst for methanol reforming (Battelle).
- Preferential Oxidation (PROX) of Carbon Monoxide (CO)
  - #20020018738, 2/14/02. Pulsed flow PROX.
  - #20010037948, 11/8/01. Regenerative adsorption and electro-catalytic (ECO) CO removal (Honeywell).
  - #20020004452, 1/10/02. PROX catalyst comprised of ruthenium on high-porosity alumina. Operating temperatures from 70C to 160C (UOP).
- Process Integration
  - #200200042035, 4/11/02. Single-pipe cylinder reformer: multiple coaxial cylinders surround a radiation cylinder with a burner at one end.
  - #20020027027, 3/7/02. Integrated thermal management on-board a vehicle via one high temp coolant circuit and one low temp coolant circuit (GM).
  - #20010002248, 5/31/01. Feed forward active control of the WGS temperature to compensate for load changes.
- Membranes
  - #20020041837, 4/11/2002. H2-selecive metal membrane; use for processing or purification.
- Combustors
  - #20020028366, 3/7/02. Recuperated anode gas oxidizer (AGO); cathode exhaust air used as oxidant (Delphi).
  - #20020022204, 2/21/02. Catalytic combustor. Combustion takes place on a heat-conductive separator that has “projections and depressions” that stabilize the combustion reaction (Toyota).
- Other Patents
  - #20010038934, 11/8/01. Reformation of a fuel/water emulsion (ExxonMobil).

4.2.3 Portable vs. Stationary Reforming

A stationary fuel processor can usually achieve superior efficiency and hydrogen quality performance compared to a portable reformer. However, this usually comes at a

price of longer warm-up time, dynamic range, response time, weight, vibration, shock, and temperature resistance, etc.

Another major advantage of the stationary processor is capacity factor - the fraction of time that the equipment is operated. A low capacity factor translates directly into higher product costs, since the equipment must be amortized over less product - in this case hydrogen. The capacity factor for an onboard reformer is less than one percent. A car typically operates for only 1 to 2 hours per day on the average, and even when it is moving, a car engine power draw averages less than 10% of rated power.

Table 7. Comparison of Fuel Processor Attributes for Stationary and Portable (after on-board) Fuel Processors

	Stationary Fuel Processor	**Portable Fuel Processor (after DOE on-board targets)**
Warm-up Time	30-120 minutes	< One minute (10sec preferred)
Dynamic Range	1.5 to 1	80 to 1
Response Time	10's of minutes	Seconds
Weight	Not an Issue	< 120kg
Vibration, shock, temperature extremes	Not significant	Automobile Environment
Capacity Factor	.69	0.0086 (hybrid) 0.0053 (pure F.C.)
CO_2 Sequestration	Possible	No
Operating Life	87,000 hrs [10 years]	3,000 hrs [125,000 miles]
Compressor and Storage Required	Yes	No

Another major advantage of stationary processors is CO_2 sequestration - it is at least theoretically possible to capture the carbon dioxide (the leading greenhouse gas) from the stationary processor exhaust and sequester that gas underground. The CO_2 emitted from millions of moving vehicles could never be captured, eliminating this option to reduce climate change gases.

The only two features of a portable fuel processor that make it an attractive product target are its typically short operating lifetime and the avoidance of hydrogen compression and storage. However, these two advantages are overshadowed by the challenges of having to design for portability, fast start-up, physical robustness, etc., most of which translate directly into increased cost for the hydrogen fuel system.

Within the hydrogen FCV category, the method of making the hydrogen is important. Hydrogen made by electrolysis of water provides a very useful initial source

for FCVs - small-scale electrolyzers can be added at the fueling station serving only a few FCVs. Unfortunately, most of the electricity in the US and most other major countries comes from coal or natural gas, so greenhouse gas emission are frequently increased by using electrolytic hydrogen in a FCV. Eventually, as some combination of nuclear or renewable electricity dominates the grid of any locality, then electrolytic hydrogen will be the optimum sustainable energy source. Until that time, the production of hydrogen by reforming natural gas or propane is one of the best alternatives to produce environmentally and economically sound hydrogen.

4.2.3.1 Reforming for Portable Power Systems

Propane is a competitive fuel for use in portable applications, as it has already proven itself as a highly useful and valued fuel in recreational vehicle auxiliary power, camping portable power, and similar applications. Consumer preference and acceptability of propane fuel for these applications together with its superior energy storage density (especially compared to hydrogen), make it a very attractive fuel for portable power fuel cell system applications.

The characteristics of a state-of-the-art reformer system for portable power, however, differ significantly from those of a stationary power reformer system. Efficiency can often be compromised for decreased size and weight (key features that are required for portable systems). In this sense, a portable power propane fuel cell system has requirements that are similar to automotive fuel cell systems that considered on-board reforming (which is no longer being significantly considered or advanced). As a result, portable fuel processing technology for propane fuel cell systems may benefit from the significant earlier investments of the automotive industry in on-board fuel processing.

Fuel cell vehicles (FCVs) under development almost invariably use PEMFCs for the power plant. The discussion below assumes that the portable propane fuel processor must produce a reformate fit for use in a PEMFC. However, it should be noted that SOFC powered auxiliary power units (APUs) are under development, and these could be used in portable power applications as well. The key limitations of these SOFC systems for use in portable power applications is start-up time and cycling lifetime. On the other hand, fuel processor requirements for the SOFC are easier to meet than those of the PEMFC.

Designing a portable propane fuel cell system is a major technological challenge. Prototype portable power systems have been demonstrated primarily as running on methanol and direct hydrogen. These systems have emerged first since steam reforming of methanol is the simplest fuel processing approach. Propane may have advantages over methanol since methanol is classified as toxic and has approximately only 2/3 the energy density of propane. It is also claimed that widespread use of methanol would require a new infrastructure that would be a distraction from the ultimate goal of building a H_2 infrastructure.

Others believe using the existing infrastructure will be key to bringing fuel cells to the portable power market. Propane will be an ideal fuel in this case. Propane has been successfully reformed using SR methods as well as ATR and POX processes. ATR and POX methods have been found to more reliably handle the impurities and odorants present in propane. Whereas both ATR and POX approaches are capable of reforming

propane, ATR is the preferred method due to its higher efficiency. The reformation of propane is considerably more difficult to manage than the reformation of methanol, but, it is also considerably easier than reforming distillate fuels. Significant advances have been made in the last few years in ATR technology. This has been demonstrated in stationary fuel cell systems (e.g., Plug Power GenSys5™) and in both stationary, fuel cell APU, and fuel cell vehicles running on gasoline, diesel or other distillate fuels.

Considerations for fuel processor components downstream of the syngas generator are almost independent of the initial reforming approach. WGS reactors provide the dual benefits of reducing CO and increasing H_2. The remaining question is whether the CO will be cleaned up and the fuel cell run on reformate gas or if the H_2 will be separated out and the fuel cell run on pure H_2. For the former case, PROX appears to be the preferred approach. For the latter case, the only type of purification process that may be practical is membrane separation as the other possible approaches are too bulky. Table 8 below shows potential advantages and disadvantages between PROX and membrane separation:

Table 8. Options for Gas Clean-up for PEM Fuel Cells.

	PROX	**Membrane**
Advantages	Cost Low Pressure Drop	Pure H_2 FC Operation Advantages
Disadvantages	Controllability	Pressure Drop Cost

4.2.4 Analyses of Potential Fuel Processing Technology

4.2.4.1 Qualitative Analysis of Fuel Processing Technology

The current conventional wisdom appears to be that ATR is the preferred approach for reforming distillate fuels. This perception is based largely on the following advantages ATR apparently has over SR: 1) Fuel flexibility. Steam reformation of hydrocarbons other than methane and methanol has been a challenge. The oxidation component of the autothermal reaction is far less selective. 2) Transient response. ATR designs are more responsive than SR designs. The fundamental factor is heat transfer. In an SR system, heat must be transferred from the “furnace” gas to the reformation reactants. In an ATR system, hot products of the oxidation reaction directly supply heat for the endothermic reactions. 3) Sulfur tolerance. Traditional iron/chrome steam reforming catalysts are poisoned by sulfur. An on-board steam reformer will have to address these issues to be successful. The plate reformer concept can potentially address the transient response issue by enhancing heat transfer. However, the heat exchangers will have to be extremely effective. Fuel flexibility and sulfur tolerance are catalyst development issues.

Zinc-oxide (ZnO) beds and upstream desulfurizers seem to be the two main categories of sulfur cleanup approaches. Upstream desulfurizers add more size, weight and cost to the system, but they have the advantage of uncoupling the sulfur cleanup step from the rest of the process. Zinc-oxide material is inexpensive, but it must be maintained in the proper temperature range for it to work. Inserting this temperature regime requirement between the reformer and WGS can complicate the overall process.

An additional challenge associated with ZnO beds is the high water content of the reformer products may actually favor the reverse of the desired reaction: $ZnO + H_2S \leftrightarrow ZnS + H_2O$.

With the availability of high, medium and low temperature catalysts, there are countless possible approaches to the WGS reaction. A single, MTS step should certainly make for a smaller, less expensive system than a two-step, HTS to LTS approach. The trade-off is achieving a low enough CO content in the WGS effluent that the PROX can reliably and consistently prepare the reformate for the FC. PROX capabilities drive WGS requirements. However, maximizing CO conversion in the WGS minimizes H_2 losses in the PROX.

For CO cleanup, PROX technology is clearly favored as of today. They offer a clear advantage to membranes with respect to minimizing pressure drop. A superior PROX catalyst will have the greatest selectivity over the widest possible temperature range. Perhaps the most significant PROX design challenge is the fact as temperature increases through a bed from the exothermic oxidation reaction, the catalyst's selectivity for CO over H_2 will decline.

4.2.4.2 Portable Fuel Processing to DOE On-Board Fuel Processing Targets

DOE's cost and performance targets for an automotive on-board fuel processor provide the most established basis for evaluating a given portable power fuel processing approach.

Table 9 shows the DOE targets for on-board fuel processing established for 2004. The most likely contributor to excessive startup time is the WGS reactor. The approach appears to be on target for the other specifications. Note that 0 ppm is not a reasonable target; achieving < 0.1 ppm H_2S in the fuel processor outlet gas should meet fuel cell requirements.

Table 9. DOE Targets for Automotive On-Board Fuel Processing

Specification	DOE On-Board Fuel Processing Targets for 2004
Startup Time @20C (Minutes)	0.5
Transient, 10%-100% Load (Seconds)	10
% Efficiency (LHV, DOE Method[1])	80
Steady State/Transient CO in FP Outlet (ppm)	<10 / <100
H_2S in FP Outlet (ppm)	0
Ammonia in FP Outlet (ppm)	<10

Table 10 presents the specific power and power density characteristics of the 2004 DOE targets for on-board fuel processing. These are very challenging targets to meet. Most of the prototypes that have been demonstrated to-date have specific power and power density numbers that are approximately an order of magnitude less than (at best

half of) these DOE targets. Note that the DOE targets also include fuel processor balance of plant (BOP) items, i.e. valves, meters, controllers, tubing, etc.

Table 10. DOE Targets for Mass and Volume of On-Board Fuel Processor

	DOE On-Board Fuel Processing Targets for 2004
Specific Power (W/kg)	750
Power Density (W/L)	750

4.2.5 U.S. DOE On-Board Fuel Processing Support

For the past decade, the U.S. Department of Energy (DOE) has sponsored research to develop onboard fuel processing systems (also known as fuel-flexible processing and quick-start reforming systems) as one option to bridge the transition to a hydrogen economy. During the transition from internal combustion engines to direct-hydrogen fuel cell vehicles (FCVs), the existing fuel infrastructure could provide readily available fuels (e.g., propane, gasoline, ethanol, methanol, and natural gas) to fuel-flexible FCVs that generate hydrogen on board the vehicle.

With the establishment of the FreedomCAR Partnership in January 2002 and the Hydrogen Fuel Initiative in January 2003 (which accelerates the hydrogen commercialization decision from 2030 to 2015), DOE recognized the need to re-evaluate this research direction and established a Go/No-Go decision milestone for June 2004. In support of this decision, DOE conducted an extensive technical evaluation of the status, progress, and potential of on-board fuel processors.

After examining the progress by fuel processor developers, the report of an independent panel of technical experts, the position papers by stakeholders, and other factors including the status of competing technologies, the DOE decided to discontinue development of on-board fuel processing for fuel cell vehicles. The rationale for the decision includes several key points: current technical targets are not being met, meeting the established targets for 2010 and 2015 is unlikely, and competing hybrid technology is entering the market today which rivals the fuel economy of what can be achieved through on-board fuel processing for FCVs. [Ho et al., 2004]

The Kuwaiti Energy Minister in October 2005 reported at the Montreux Energy Conference in Washington DC that his country will be joining with ARAMCO to fund a $100M on-board fuel processing R&D program. OPEC countries have a vested interest in the continued use of petroleum based and refined products as the fuel cell source for the global transportation sector. Therefore, ARAMCO is seeking to revive the on-board fuel processing R&D.

Nonetheless, the technology that was developed by organizations who were funded by this DOE program could be directly applicable to ARAMCO and PERC propane reforming interests. The key features of fuel flexibility, sulfur handling, light weight and compact, fast start-up, etc. are all applicable to the primary applications where propane fuel cell technology could be applied. As a result, the authors recommend PERC review and take interest in the advances of companies previously supported by the DOE on-board fuel processing development program as well as those companies that are funded by ARAMCO in the future.

For completeness, the status of on-board fuel processing is presented in Table 11. Note that these technical features are desirable for portable propane fuel processors. In addition, note that the performance achieved to-date is impressive, suggesting that the less stringent criteria for portable power may be reachable. However, there is no evidence that any one type of system could simultaneously achieve all of the values indicated in the Current Status column. So care must be taken when reviewing these overall performance numbers.

Table 11. 2004 Demonstration Criteria, Ultimate Targets, and Status of On-board Fuel Processing[1] [Ho et al, 2004]

Attribute	Units	Current Status (2/2004)	2004 Demo Criteria	Ultimate Target	Probability of Reaching Ultimate Target
Durability	hours	1000	2,000 and > 50 stop/starts	5,000 and 20,000 stop/starts	high
Power Density	We/L	700	700	2000	medium
Efficiency	%	78	78	>80	high
Start-up Energy	MJ per 50 kWe	7	<2	<2	low
Start-up Time (+20°C)	seconds	600	<60 to 90% traction power	<30 to 90% <2 to 10%	low
Transient Response	seconds	10	<5, 10% to 90%, and 90% to 10%	<1, 10% to 90%, and 90% to 10%	low
Turndown	ratio	20:1	20:1	> 50:1	high

[1]This table generally identifies the best performance by any of the evaluated systems.

5 Industrial Sector Issues

5.1 Assessment of Propane Oriented Fuel Cell Companies

Report on companies that are currently developing propane-powered fuel cells and their status with respect to commercialization. Advise as to which companies PERC should be partnering.

Fuel processor technology has been significantly advanced in recent years with the intense interest in developing and using fuel cell systems. This is especially true for the technology associated with the production of rather pure hydrogen streams for use in lower temperature fuel cell systems. The advancement has been most significant for these lower temperature fuel cell systems because of the more significant investment in technologies such as proton exchange membrane fuel cells as well as the fact that more of these types of systems (e.g., PEM and PAFC) have been manufactured to-date.

Several companies have emerged recently to become leading developers and manufacturers of fuel cell fuel processing technologies. Although not all of these companies have expertise that is directly applicable to propane fuel processors, each has advanced technology that could be characterized as generally applicable to propane fuel processors that should be of interest the Propane Education & Research Council.

This section summarizes some of the more recent advances and highlights the major fuel processing companies who have emerged as leading developers of fuel processing technology that could be or has already been applied to propane fuel.

5.1.1 Major Fuel Processor Development Organizations

A summary list of the major organizations that are advancing fuel processor technology is presented in Table 12 . Note that this list is not comprehensive, but rather, representative of the set of organizations that have recently emerged with fuel processing capabilities that could be applicable to the development of propane fuel processors and fuel cell systems. The final column of Table 12 indicates whether or not the literature directly states, or the authors otherwise know about experience that the organization has with the use of propane in a fuel processor. Whenever a check mark (✓) appears in this column, some degree of experience with the processing of propane for use in a fuel cell is present within the organization.

Table 12. State-of-the-Art Fuel Processor Development Organizations (not comprehensive).

Organization	Location	General Areas of Expertise	Propane Experience
Acumentrics	Massachusetts, USA	Fuel processing, tubular SOFC	✓
Air Products and Chemicals, Inc.	Pennsylvania, USA	Fuel processing, hydrogen production, purification, storage and transport	
Argonne National Laboratory	Illinois, USA	Fuel processing, liquid fuels, PEM, MCFC, and SOFC	✓
BP	UNITED KINGDOM	Fuel processing	
Catalytica Energy Systems, Inc.	California, USA	Catalysts and fuel processing	✓
ChevronTexaco	California, USA	Fuel processing	
Ceramic Fuel Cells Ltd.	Noble Park, AUSTRALIA	SOFC, fuel processing	✓
Cummins/SOFCo	Utah, USA	SOFC, Fuel processing, recreational vehicle application	✓
Delphi Corporation	New York, USA	SOFC, Fuel processing, APU	
EBARA Ballard Corporation	Tokyo, JAPAN	Fuel processing, PEM	
Energy Research Center of the Netherlands (ECN)	Netherlands	Fuel processing,	✓
Englehard Corporation	Iselin, USMOI	Catalysts, fuel processing	
ExxonMobile Corporation	New Jersey, USA	Liquid fuel processing	
FuelCell Energy, Inc.	Connecticut, USA	MCFC, SOFC, fuel processing	✓
Fuel Cell Technologies, Ltd.	Ontario, CANADA	Fuel processing, SOFC	
GE Hybrid Power Systems	California, USA	Fuel Processing, SOFC, Hybrid	
GE Energy	New York, USA	Fuel Processing, SOFC, PEMFC	✓
GE Global Research	California, USA	Fuel processing, PEM, SOFC	✓
Hydrogenics Corporation	Toronto, CANADA	Fuel processing, PEM	
IdaTech	Oregon, USA	Fuel Processing, PEM	✓

InnovaTek, Inc.	Washington, USA	Military fuel processing	
Intelligent Energy, Inc.	California, USA	Fuel Processing, PEM	✓
Korea Institute of Energy Research	Daejeon, KOREA	SOFC, Fuel Processing	✓
Los Alamos National Laboratory	Illinois, USA	Fuel processing	
McDermott Technology, Inc.	Ohio, USA	Military fuel processing, PEM, SOFC	✓
Mesofuel, Inc.	New Mexico, USA	Compact and military fuel processing	
Mitsubishi Materials Corporation	Ibaraki, JAPAN	SOFC, fuel processing	
National Energy Technology Laboratory	West Virginia, USA	Fuel processing, SOFC	
National Fuel Cell Research Center, UC Irvine	California, USA	Fuel processing, SOFC, MCFC, PEM	
N-GHY S.A.	Albi, FRANCE	Steam reformation	✓
Nu Element, Inc.	Washington, USA	Military fuel processing, PEM	
Nuvera Fuel Cells	MA, USA	Fuel processing, PEM	✓
Osaka Gas Corporation	Osaka, JAPAN	Fuel processing, PEM, SOFC	✓
Pacific Northwest National Laboratory	Washington, USA	Compact fuel processing, PAFC, MCFC and SOFC	
Praxair	New York, USA	Fuel processing, hydrogen production, purification, storage and transport	
Precision Combustion, Inc.	Connecticut, USA	Catalytic combustion, fuel processing	✓
Plug Power, LLC	New York, USA	Fuel processing, PEM	✓
Shell	NETHERLANDS	Fuel processing	
Siemens Westinghouse Power Corporation	Pennsylvania, USA	SOFC, fuel processing	✓
TMI	Ohio, USA	Fuel processing, SOFC	
Tokyo Gas Corporation	Tokyo, JAPAN	Fuel processing, PEM, SOFC	✓
UTC Fuel Cells	Connecticut, USA	Fuel processing,	✓
ZBT, GmbH	Duisburg, GR	Fuel processing, PEM, APU	✓

5.2 Recommendation of Companies with Competencies for Addressing Propane-Oriented Fuel Cell R&D Priorities

Determine the technical issues specifically related to propane that must be addressed and recommend the companies that possess the expertise and disposition to address these issues.

Fuel processor integration with the fuel cell is of the utmost importance. The two subsystems must be inextricably linked to achieve both maximum efficiency and general functionality. Integrating a fuel processor with a PEM fuel cell stack may not involve significant physical integration, i.e. combining fuel processor and fuel cell functions into single pieces of hardware. However, integration with respect to how the two systems work together will be crucial. Thus, the team has focused on fuel processing as the technical issues specifically related to propane that must be addressed, and therefore has become the primary criteria for any recommendation of companies that possess the expertise and disposition to address these issues.

Start by considering normal steady state operation, at any given load. The fuel cell manufacturer has designed his stack to operate at a specific temperature, a specific pressure, a specific maximum allowable CO concentration and a specific minimum allowable H_2 concentration (to meet power delivery expectations). These requirements will be unique to the specific fuel cell stack design. The fuel processor must be able to deliver reformate that meets these specifications.

The overall system startup and shutdown sequences are also an issue. The fuel processor and fuel cell must be integrated from a control system standpoint to ensure starts and stops occur reliably, without damaging hardware or creating unsafe conditions.

Meeting load following requirements will also require close integration. Both hardware and software may be affected. If the fuel cell tries to ramp up power delivery more quickly than the fuel cell can ramp up H_2 production, cell voltages will drop as H_2 utilization climbs towards 100%. If the fuel cell ramps down power delivery too quickly, excess H_2 will be recycled back to the fuel processor, possibly causing overheating in the anode gas oxidation zone. The process is complicated by the fact that while H_2 delivery rate is changing, the characteristics of the reformate gas will still have to meet certain requirements, particularly with respect to CO concentration. Integration will be key as different fuel cell systems will be designed for different applications, each with its own load following requirements.

Thus integration between the fuel processor and the PEM fuel cell is definitely of significance. It is true that pursuing a more generic design would benefit from economies of scale in production. However, optimizing a fuel processor design to meet the requirements of a specific fuel cell stack may result in more cost savings. The generic design would have to meet the requirements of every fuel cell stack it might be integrated with. Such sophistication could result in further costs.

In contrast to PEM integration, physical integration is required in a SOFC system. The endothermic reforming reaction is used to cool the exothermic electrochemical reaction in the fuel cell stack. Thus the high temperature fuel cells (SOFCs and MCFCs) utilize “internal” reforming. However, the SOFC may require an external reformer (pre-reformer) for startup.

For an automotive APU application, this pre-reformer may allow for a more physically separated design.

Significant progress has been reported in the development and limited commercialization of PEMFC systems operating on hydrogen, methanol, natural gas, and even LPG to a limited degree. There have even been reports of successful reformate generation and use in fuel cells from liquid fuels, such as gasoline, diesel, and military fuels. However, there is substantial work to be done before one can build a practical PEMFC system that operates on fuels of importance for defense applications—typically aviation fuels (JP8 and JP5) and diesel.

In this section of the report, technical advances and reports on the state-of-the-art fuel processing technology from the major companies and other development organizations are provided. Results are presented in alphabetical order of organization name.

5.2.1.1 Acumentrics

Acumentrics is leading one of the SECA Industrial Teams described in more detail above. These Industrial Teams are advancing SOFC stack and system technology aimed at low cost, modular fuel cell technology development and commercialization. Acumentrics uses a micro-tubular design and is already offering early units for field testing. It is interested in the IT and UPS market. It has conducted over a dozen early unit field tests. The advantages of smaller diameter Acumentrics tubes are higher volumetric power density and rapid start-up (less susceptible to thermal shock). They have already achieved 63 thermal cycles. [Williams et al., 2004]

5.2.1.2 Catalytica Energy Systems, Inc.

Catalytica Energy Systems, Inc. (CESI) has designed, built and tested a 3 kW(e) steam reformer prototype system using a plate-based reactor design approach. In addition, CESI developed a detailed model of the system to garner insights into the design for improvement. Pre-existing corrugated heat exchanger plates were modified and welded together to assemble a plate stack with alternating reforming and combustion channels. Supporting balance of plant components have been developed, built, and integrated into the prototype system. The unit was successfully tested. Test results demonstrated a 70 second start-up time, a 20:1 turndown ratio, and a 20% load change within 1 second. Current development in the control system should allow for improvement in all these areas.

These results validated the model which was used to garner insights into the design and operation of the plate-based reformer design. By acting both as a heat exchanger and as a reactor in a single unit, a plate reactor reduces the number of external heat exchangers in an integrated fuel processor system. In the steam reforming reactor, the separation of the steam reforming and combustion streams permits the reforming process to be conducted at a higher pressure than the combustion, thereby eliminating costly gas compression. The separation of the two streams also prevents the dilution of the reformate by the combustion air. The heat generated on the combustion side of the plate is efficiently transferred across the thin plate to drive the endothermic reforming reaction occurring on the reforming side of the plate. [Nicole et al., 2004]

5.2.1.3 Ceramic Fuel Cells Limited

Ceramic Fuel Cells Limited (CFCL) is developing micro-CHP units in the size range 1 to 10 kW. The first field test units are designed to produce 1kW of electricity and supply the hot water needs of a residential customer using natural gas fuel. High system efficiency is a key design objective – a significant challenge in small systems such as residential CHP units, and involves low thermal losses through very tight integration of hot BOP components, as well as low parasitic losses through highly efficient electrical system components such as fuel/air blowers, inverter and control system. Over the past 12 months, CFCL designed, constructed, commissioned and tested two System Demonstrators and one 1kW residential CHP prototype (CHP-1). The primary objective of the demonstrations is to characterize stack performance in a system environment and to verify BOP components and control strategies. CFCL recently completed a 4000 hour test on propane fuel in one of the demonstrators. Operational modes of start-up, controlled shut-down, operation producing AC output have been successfully demonstrated including one uncontrolled emergency shutdown. [Dinsdale, Conduit, and Foger, 2004]

5.2.1.4 Cummins/SOFCo EFS

Cummins and SOFCo EFS previous led one of the SECA Industrial Teams that is advancing SOFC stack and system technology aimed at low cost, modular fuel cell technology development and commercialization. Cummins has now been contractually teamed with Versa Power, and SOFCo are pursing separate interests. The mission remains for developing a 10 kW product initially for recreational vehicles that would run on propane using a catalytic partial oxidation reformer as well as a stationary unit. The team has produced a conceptual design for a multilayer SOFC stack assembled from low-cost "building blocks." The basic cell, a thin electrolyte layer (50-75 micron), is fabricated by tape casting. Anode ink is screen-printed onto one side of the electrolyte tape, and cathode ink onto the other. The printed cell is sandwiched between layers of dense ceramic that will accommodate reactant gas flow and electrical conduction. The assembly is then co-fired to form a single repeat unit. [Williams et al., 2004]

5.2.1.5 Delphi

Delphi is leading one of the SECA Industrial Teams that is advancing SOFC stack and system technology aimed at low cost, modular fuel cell technology development and commercialization. Delphi is close to meeting its Phase 1 SECA technology performance targets. Its 3rd generation design has achieved 420mW/cm^2 in a 30-cell fuel cell stack (2 stacks). Delphi, in partnership with Battelle/PNNL, the world's leading SOFC laboratory, is developing a 5 kW, planar, 700C - 800C, anode-supported SOFC compact unit for the distributed generation and auxiliary power unit markets. Delphi is expert at system integration and high-volume manufacturing and cost reduction. They are focused on making a very compact and light-weight system suitable for auxiliary power in transportation applications. [Williams et al., 2004]

5.2.1.6 Energy research Centre of the Netherlands (ECN)

Current research and development at ECN includes the SOFC and PEMFC, fuel processing and system development. The research projects address two major applications micro/mini CHP (Combined Heat and Power), and fuel cell vehicles. Niche markets are addressed as well, since they are considered important stepping-stones in the

commercialization of fuel cell technology. For niche markets such as generators for yachts and electricity production at remote sites, both hydrogen and natural gas typically are not the fuels of choice. Therefore, ECN has now included LPG and propane reforming in its R&D program. This logic is directly applicable and relevant to PERC goals for fuel cell system development and application.

ECN is quite well known for its research and its granting of technology licenses in exclusive or non-exclusive arrangements, depending on the situation. In some cases, ECN establishes a spin-off company to commercialize its technology. InDEC, was established in this fashion in 1999, to operate a pilot plant for the production of components for solid oxide fuel cells based on ECN technology. In 2003, the Bayer subsidiary H.C. Starck acquired the majority of InDEC shares, which is considered an important step towards the commercialization of SOFC technology. A second example is the company SulphCatch, established in 2004. SulphCatch BV is owner of a new technology developed by ECN that efficiently removes the odorant THT from natural gas. Each of these companies, as well as the current research and development activities at ECN should be of interest to PERC.

In the area of fuel processing, research is focused on the development of catalysts, catalyst support structures and reactor designs for the reforming of logistic fuels, their upstream desulphurization and, for PEMFC applications, the downstream gas-cleanup to obtain clean hydrogen feeds of fuel cell quality. For micro-CHP or backup power applications, ECN focuses on fuel processing of natural gas and LPG. For transport applications, especially APUs, research is focused on reforming of heavier middle distillate fuels, such as (marine) diesel.

In the area of reforming, research focuses on catalyst and reactor development for Auto Thermal Reforming of propane and diesel. Reactor development for the ATR of diesel resulted in designs showing robust operation in terms of mixing, fuel evaporation and coke deposition up to several hundreds of hours. Catalyst development aims at improved performance for reforming of higher hydrocarbons with respect to activity, selectivity, lifetime and costs. [Mallant, and van den Oosterkamp, 2004]

5.2.1.7 Engelhard Corporation

Engelhard Corporation is well known for development and commercialization of catalysts for a wide variety of applications. These applications include all types of catalysts used in the development of fuel processor systems. Recently, Engelhard researchers have advanced catalytic steam reforming (SR) as an attractive process to convert hydrocarbons into hydrogen used in fuel cells as it produces a reformate with significantly higher hydrogen concentration than other reforming methods. But, the SR reaction is highly endothermic and therefore requires large reactor surface areas for heat transfer and a high operating temperature to achieve higher conversion.

Metallic monoliths are routinely used in automotive converters for fast start-up. Adhesion of catalyst washcoat on metal substrates used in high temperature applications is generally improved by pretreating and activating the substrates to increase the bonding between washcoat and the metal substrates. Though the technology for washcoating combustion catalyst onto metallic substrates is rather mature, adjustment in washcoat formulation and metal materials selection are required for steam reforming where high temperature and high steam concentration are present in a reducing atmosphere, and in some applications high pressure is involved.

Based on Engelhard's extensive experience with automotive converters on metal substrates, steam reforming catalysts with excellent adhesion and stability can now be prepared. The current catalysts are precious metal-based. Manufacturing includes washcoating the catalyst onto a FeCrAlloy monolith. During steam reforming of methane at a 700C inlet is required and an air flow was periodically injected into the reaction stream. This periodic air flow injection created temperature spikes that changed the catalyst temperature quickly from 600C to 900C (to stress the adhesion of the catalyst to the monolith). After 120 such thermal stresses, the sample maintained a steady performance and loss in washcoat was negligible when comparing the sample weight before and after the test. [Liu and Farrauoto, 2004]

5.2.1.8 ExxonMobil Corporate Strategic Research

ExxonMobil researchers have recently developed a novel method of hydrogen production that they claim is suitable for mobile, small-scale, and potentially large-scale manufacture of hydrogen. The technology is dubbed Pressure Swing Reformer (PSR), which utilizes a steam reforming process that yields high-pressure, undiluted syngas from low-pressure air at high efficiency, with the compactness of an autothermal reformer. PSR is a cyclic process that alternates low-pressure combustion cycles to heat the reforming catalyst bed with high-pressure reforming cycles that cool the bed. During these cycles the center of the catalyst bed remains quite hot - the peak temperature can be 1000-1200C - but the inlet and exit to the reactor, as well as the metal reactor wall remain relatively cool – typically below 400C. PSR avoids the critical heat-transfer issues of conventional steam reforming by performing heat transfer internal to the reactor within the catalyst bed. The high-pressure product enables high-purity separation systems such as pressure-swing adsorption or membranes to yield a pure hydrogen product that can be utilized in a PEM fuel cell.

PSR technology is claimed to have superior size, start-up time, and start-up energy requirements compared to other fuel processor types. The PSR approach eliminates most of the components of a typical PEMFC fuel processing system. The reformer, as well as the inlet and exit heat exchangers, are all incorporated into the PSR reactor bed. Since only the internals of the PSR reactor need to be heated for the system to function, the overall thermal mass of the system is relatively small, and is heated directly and efficiently by the combustion of fuel on the reforming catalyst. The system is designed to use low-pressure cathode tail-gas as the air supply, eliminating the need for a separate compressor to run the fuel processor; the anode tail-gas and separator purge are used as the fuel input needed for steam reforming. The entire system can be heat balanced with only minimal water-gas shift. Thus, it can be integrated directly with the fuel cell stack, providing system simplicity and reducing overall size, weight, and cost.

The combination of PSR with a simple hydrogen separation step leads to an overall hydrogen production scheme that is efficient, compact, can start quickly, has a very low start-up energy requirement, and is capable of rapid transient response. This makes the system ideal for small-scale applications where the fuel cell may be moved (e.g., vehicles, portable power, and distributed power). [Berlowitz et al., 2004]

5.2.1.9 Fuel Cell Energy and Versa Power Systems

FuelCell Energy (FCE) and Versa Power Systems, along with their partners, are engaged in the development of a thermally integrated, high power density SOFC generator. As previously mentioned above, they have been contractually merged with Cummins Power for

the DOE SECA program. Their near-term focus is to develop 3-10 kW size SOFC system for stationary power applications using natural gas fuel. In the long-term, multi-fuel capability to include diesel and propane fuels will be added. Power plants larger than 10 kW are envisioned to be built with multiple units of basic 3-10 kW modules. Significantly, this technology is being developed with propane fuel use in mind and with the significant expertise and background of the former Global Thermoelectric, Inc. This should be of considerable interest to PERC. [Patel et al., 2004]

FCE molten carbonate fuel cell technology in general is very fuel flexible. However, the size range of their current product line (> 250kW) does not make it cost effective or amenable to propane fuel use. Nonetheless, FCE continues to enhance their product lines capability. The ability to operate on more than today's standard natural gas or anaerobic digester fuels will be available soon. These additional fuels will include propane, diesel fuel, coal derived gas, and industrially available hydrocarbon off-gasses. Combined cycle applications with the DFC/T® concept, that approach 70% electrical efficiency, are in the engineering design phase and demonstration projects are expected in the near future. [Skok, Oei, and Nock, 2004]

5.2.1.10 GE Energy

The solid oxide fuel cell (SOFC) technology under development at General Electric (GE) Hybrid Power Generation Systems is based on a planar design that incorporates anode-supported cells and metallic interconnects and operates at about 800°C. GE has been evaluating two systems based on this technology: ambient-pressure, simple-cycle SOFC and pressurized SOFC/gas turbine (GT) hybrid systems. For the simple-cycle system, GE has been developing a 3-to-10-kW prototype system operating on natural gas. Current activities in this area encompass system design and analysis including controls, SOFC technology development including design, performance, and lifetime improvements, and balance of plant (BOP) assessment and evaluation. For the SOFC/GT hybrid system, GE has been developing and assessing system concepts (up to MW class) and demonstrating operation of planar SOFC stacks under pressurized conditions. GE has also developed state-of-the-art reformers based on CPO and ATR approaches. An autothermal reforming (ATR) fuel processor for the prototype SOFC system has been designed, built and tested on natural gas and propane and meets the system requirements. [Minh, 2004]

5.2.1.11 Idatech

IdaTech is a company that PERC is quite familiar with. PERC has funded IdaTech to develop and demonstrate propane fuel cell technology for several years. IdaTech is well known in the fuel cell community for fuel processing and PEMFC systems integration expertise. IdaTech is probably most well known for its experience with a wide variety of fuels that it has used in its fuel cell systems.

In addition to PERC funding, IdaTech has recently been funded by the U.S. Navy, Naval Surface Warfare Center to develop and demonstrate a 2 kW (net electrical) PEMFC system that operates on kerosene2 or diesel fuels. The system design incorporates IdaTech's compact fuel processor (steam reformer combined with membrane-based hydrogen purification) and IdaTech's PEMFC power module. Fuel desulfurization is accomplished using a conventional reactive-metal absorbent to protect the steam reforming catalyst from poisoning (there is no risk of poisoning the fuel cell stack because a hydrogen-selective membrane is used to purify the hydrogen and reject all impurities in the reformate stream).

Overall system simplification is a direct result of the production of high purity hydrogen by the fuel processor module (typical hydrogen purity exceeds 99.95% with <1 ppm CO and <3 ppm CO_2). The sulfur-removal cartridge has been designed as a field-serviceable component. Using low sulfur fuels, the operational lifetime of the cartridge is expected to exceed 100 hours between servicing. Longer operating periods can be achieved by sizing the sulfur absorbent cartridge accordingly.

To reduce the overall size, the PEMFC power module has been redesigned to be more compact—many components have been eliminated and a non-aqueous coolant is utilized. IdaTech's current PEMFC stack, operating at exceptionally low cathode pressure to minimize parasitic power requirements, has demonstrated more than 2000 hours of operation while equaling or exceeding the beginning of life performance specifications. [Edlund, 2004]

5.2.1.12 InnovaTek

InnovaTek is well known for developing and demonstrating integrated military fuel processor technology. Recently, InnovaTek has been developing a diesel fuel reformer based on the steam reforming process for applications in the power range of 1-5 kW. After successful demonstration of their first prototype system in 2002 [Ming et al., 2003], the system has been further optimized by redesign of the major components, emphasizing compactness, improved thermal and mass transfer, and system efficiency. The reactor design has been engineered to provide a very high surface to volume ratio for improving heat transfer while maintaining the compactness of the reactor. The reactor is built on micro-channel structure that allows rapid heat and mass transport, thus providing the potential to meet the requirements of small size & volume, quick start up and rapid response to changes in hydrogen demand. InnovaTek's recent accomplishments include development, design, and demonstration of reformer reactors, an engineered catalyst, a miniature diesel and steam mixer/injector of novel design, and compact heat exchanger developments as incorporated in integrated fuel processor systems. [Ming et al., 2004]

5.2.1.13 Mesofuel, Inc. (now part of Intelligent Energy, Inc.)

Bio-fuels continue to be viewed as an alternative to fossil fuels for power production using fuel cells, thanks to potential benefits associated with the environment, the energy sector, and with national security. Mesofuel has been developing hydrogen generation systems that produce pure hydrogen (> 99.9% purity, CO free) from biodiesel and ethanol, and have demonstrated pure hydrogen production in a stable and reliable fashion. Power production by routing the hydrogen to a PEM fuel cell has been demonstrated. Both of these fuels are viable alternatives to fossil fuels for power production in agro areas and have the potential to further fuel cell use in those areas. [Chellappa, Vencill, and LaMont, 2004] Similar Mesofuel technology may be applicable to propane fuel processing.

By integrating the functions of hydrogen production and hydrogen separation in a membrane steam reformer, pure hydrogen can be produced in a single compact unit that is particularly attractive for power applications in the < 100 kW range. Mesofuel has demonstrated pure hydrogen production from a wide range of hydrocarbon fuels in the C1 to C12 range in an efficient manner using steam reformation, while operating at 575 to 625 ^{o}C and 6 bar. Sulfur traps are used for removing sulfur from common fuels such as gasoline while operating at ambient conditions using novel adsorbents.

To-date, Mesofuel has demonstrated pure hydrogen (> 99.96% purity) production at rates of 300 to 500 sccm from hydrocarbons such as methane, propane, a clean synthetic kerosene fuel, from oxygenates such as methanol and ethanol and from ammonia. They have accumulated an overall testing time of more than 1500 hours on a single multi-fuel system. They have also demonstrated pure hydrogen production during switching of fuels at operating conditions, a feature that is termed "hot swapping" of fuels. Hydrogen purity was maintained during these hot swapping events with CO levels maintained below 10 ppm and purity greater than 99.99%. [Chellappa et al., 2004]

Since April 2004, MesoFuel, Inc. is a wholly owned subsidiary of Intelligent Energy (www.intelligent-energy.com).

5.2.1.14 N-GHY S.A.

For some specific applications and niche markets, there is a strong need for devices able to produce pure H_2 from heavy fuels with pure O_2 and H_2O as oxidants. N-GHY S.A., Fuel Processors for Fuel Cells, established in early 2002, is working to develop such technology. Over the last 7 years, the N-GHY team has developed a unique process of H_2 generation from heavy fuels. The process requires no reformer catalyst to achieve high performance, and is simple, fuel-flexible, and particularly well tailored to these applications. The process primarily consists of high temperature hybrid steam reforming technology. [Marty and Grouset, 2003]

Pure H_2 production from hydrocarbons involves a H_2/CO_2 separation step, via a metallic membrane for example. The technology being developed by N-GHY makes use of a high pressure diesel fuel processing unit fed with pure O_2. The main advantage of the process developed by N-GHY is that the use of pure O_2 leads to a significantly higher efficiency compared to the use of air: conversions are complete and energy efficiencies higher than 85% can be reached. The process also has the ability to reform heavy fuels, due to the non-catalytic nature of the process. Finally, this strategy allows for the possible capture and storage of CO_2. Recently, reforming tests were successfully conducted without preheating of the reactants on a test bench rating a thermal power of 25 kW at pressures up to 6 bar, with O_2 contents enriched up to 75% vol. in the air. Liquid and gaseous fuel testing was accomplished. Fuels tested to-date are: propane, methane, ethanol, rapeseed oil methyl ester, crude rapeseed oil, sunflower oil methyl ester and diesel fuel. [Marty et al., 2004]

5.2.1.15 Nippon Oil

As previous noted, Nippon Oil has developed four different catalysts for use in kerosene and propane fuel cells applications, and has one of the largest propane fuel cell demonstrations programs in the world. Over 100 units have been installed in unit sizes of 750 W (in collaboration with Sanyo), 1 kW (in collaboration with Ballard and 1-10 kW (kerosene fueled, in collaboration Mitsubishi Heavy Industries). At the 2005 Fuel Cell Seminar, Spencer Management reiterated PERC's interest in receiving one or more of the Nippon units for field testing in the US. Nippon Oil is grateful for the continued interest in all of their propane related products, but they remain undecided as to when they will be releasing their fuel cell systems for testing outside of Japan. Nippon Oil recently reported 34% AC electrical efficiency, 76% total efficiency in the CHP configuration for their 750 W propane fueled unit. They also reported a catalyst life of 40,000 hrs which is outstanding compared to their competitors.

Data supplied by Nippon Oil in August 2006 indicated that US$60M/year of propane fuel cell leasing is current ongoing or planned in Japan with propane fuel. This represents 23% of the Japan national total of US$260M/year. Kerosene fueled systems represents another US$60M, or 23%, and City Gas represents US$100M/year, or 54%. There are total of 611 LPG units under lease contract, 75 kerosene units under lease contract and 491 city gas units under lease contract. As indicated in Table 1, all of the leased units for LPG and Kerosene are with Nippon Oil as the principal supplier, and Tokyo Gas is the principal supplier for the city gas units.

Table 1 Characteristics of the Japanese Residential Fuel Cell Market (2006)

Fuel type	LPG	Kerosene	City Gas
Principal suppliers	Nippon Oil	Nippon Oil	Tokyo Gas
Japan Energy	Osaka Gas		
Idemitsu	Toho Gas		
FC makers	Sanyo Toshiba	Ebara Ballard	Matsushita
Ebara Ballard			
Sanyo			
Price of leasing	US$ 60 M/ year	US$ 60 M/ year	US$ 100 M/ year
Estimated Sales Units (2006)	611 Units	75 Units	491 Units

5.2.1.16 Precision Combustion, Inc. (PCI)

PCI has recently advanced a “Short Contact Time” (SCT) reactor design approach that allows for the fabrication of reformers capable of overcoming current barriers of cost, size, weight, complexity and efficiency associated with more conventional reactor design approaches. PCI has developed SCT based approaches using a patented substrate and proprietary coating technology (trademarked Microlith). To-date the partial oxidation and auto thermal reforming of gaseous and liquid fuels including natural gas, propane, diesel, JP-8, Jet-A and methanol have been demonstrated. In addition, Microlith-based water gas shift (WGS) and preferential CO oxidation (PROX) reactors have also been demonstrated for multiple fuel processing applications. The Microlith substrate consists of a series of ultra-short–channel-length, low thermal mass, catalytically coated metal meshes with very small channel diameters. The ultra short channel length Microlith substrates are shown to be short enough to avoid substantial boundary layer buildup.

In high temperature reforming reactions the selectivity of the overall process is determined not only by the properties of the catalyst but also by the transport properties of the substrate. The heat and mass transport properties of the substrate can exert a significant impact on reactor performance and size. Additionally, resistance to coking, especially at low H2O:C ratios, has been observed with the short contact time reactor design. Selectivity advantages for kinetically controlled reactions such as WGS and PROX have also been observed through the use of Microlith substrates. Examples include low methanation

selectivity in WGS applications and extended operating windows for PROX at very high space velocities.

Significantly, PCI has been able to demonstrate dry and wet reforming of liquid and gaseous fuels over their Microlith substrates. Microlith based fuel reforming has also been demonstrated with military logistic fuels, with high sulfur content, as well as low sulfur diesels for transportation applications. [Roychoudhury, et al., 1997; Lyubovsky, M., et al., 2003; Roychoudhury, et al., 2004]

5.2.1.17 Siemens Westinghouse Power Corporation

Siemens Westinghouse Power Corporation (SWPC) is leading one of the SECA Industrial Teams that is advancing SOFC stack and system technology aimed at low cost, modular fuel cell technology development and commercialization. SWPC is developing 5-10 kW products to satisfy multiple markets. SWPC has developed a new tube design for their 5 kW units that use flat, high power density (HPD) tubes. This allows for a shorter tube length and twice the power output compared to their current cylindrical tube. Siemens Westinghouse's HPD flattened tubes have achieved a respectable 262 mW/cm^2 @ 85% U_f at 1000C. [Williams et al., 2004]

5.2.1.18 TMI

In 2003, TMI received two awards from the Ohio Department of Development to accelerate the commercialization of SOFCs within the state. These programs will allow TMI to demonstrate a fuel cell system that can raise the public awareness of Ohio-based companies, educational institutions, and consumers of the opportunities and benefits the emerging fuel cell industry in Ohio. Design and fabrication of a 3-kW demo system is underway. The system will have the ability to be demonstrated at multiple public sites with a variety of fuels including natural gas and propane. [Lee et al., 2004]

5.2.1.19 Toshiba

The previous text has noted Toshiba's accomplishments.

5.2.1.20 U.S. Army Corps of Engineers - ERDC-CERL

The U.S. Army Corps of Engineers - ERDC-CERL has conducted fuel cell research, development and demonstration programs for more than 12 years. Their current stationary DoD PEMFC system demonstration program currently encompasses a total of 83 PEM units that are installed at 42 sites. Contract awards to a total of five different PEMFC system manufacturers have been made, and the first units were installed in January of 2002.

The fleet of fuel cells has logged more than 276,458 operating hours, with an unadjusted availability of 87.27%. The availability for these units has ranged from a high of 98% to a low of 42%. One system achieved 100% availability for the final four and a half months of its demonstration period. It was found that the availability in the early projects depended on the accessibility of the demonstration site to the manufacturer. With later projects, though, improvements in product reliability, service person training, and real-time data acquisition systems, availability improved at sites located farther from the manufacturer.

Significantly, several of the PEMFC systems installed in this program have been operated on propane fuel. These units have been designed, built and installed by Plug Power and have

achieved an average overall efficiency of 45.70%, with an average electrical efficiency of 24.10% and an average thermal efficiency of 21.58%, based on the Lower Heating Value (LHV) for propane. [White et al., 2004]

5.2.1.21 ZBT GmbH

ZBT GmbH is working with the Centre for Fuel Cell Technology in Duisburg to develop a 300 Watt PEM system powered by liquefied petroleum gas (LPG) with primary application to the APU of leisure boats. An excellent infrastructure is available for LPG in the domain of recreational activities and users are familiar with the safe handling of liquid gas. Due to low battery capacities, the use of electric consumption on sailing yachts is quite restricted. ZBT's APU consists of a compact desulfurization unit, a miniaturized fuel processor based on steam reforming, a CO purification module, a fuel cell stack and necessary peripheral components. The ZBT APU will be able to reach high efficiencies due to the use of fuel cell anode off gas in the burner of the reformer and efficient heat integration. The overall system efficiency will be approximately 20 %.

The ZBT reformer consists of several heat exchangers, a catalytic burner and the reformer reactor itself. For system start up the burner is operated with LPG, ignited by an electrode. Under full load the burner feed includes the fuel cell anode off gas and LPG in addition. Reformer operating conditions are defined by an outlet temperature of about 650°C and a steam to carbon ratio of 3. The results from testing of the ZBT fuel processor suggest that LPG fuel processing may have a promising market in the field of leisure range applications. The complete ZBT APU system including the optimized fuel processor, the fuel cell and the peripheral components will be integrated and tested within the next year. [Beckhaus et al., 2004]

5.2.2 Recent Public Announcements

Highlights concerning progress in the area of fuel processing/reforming that has occurred over that last 5 years presented in Appendix 3.

5.3 Financial Viability of Propane Fuel Cell Companies

Assess the financial wherewithal of companies currently involved in propane fuel cell development. Determine which companies have the resources to be viable in years to come.

It is more difficult to develop similar information on non-publicly traded companies or small divisions within a large corporation. In these instances, an assessment can be made on the senior management support for the company and known sources of external funding such as DOE or other publicly announced joint ventures and partnerships. The majority of the Japanese companies involved in propane fuel cells are divisions of extremely large industrial and consumer electronics companies that are heavily subsidized and coordinated by the Japanese government. However, Spencer Management has advised other clients that there will be probably be a 50% attrition rate of Japanese companies due to the ferocity of competition for the residential market and technological failures. Gaining access to demonstration and test results will dramatically increase PERC's ability to forecast the surviving competitors, for it is Spencer Management's believe that "volume manufacturing does not cure all if the technology is inferior".

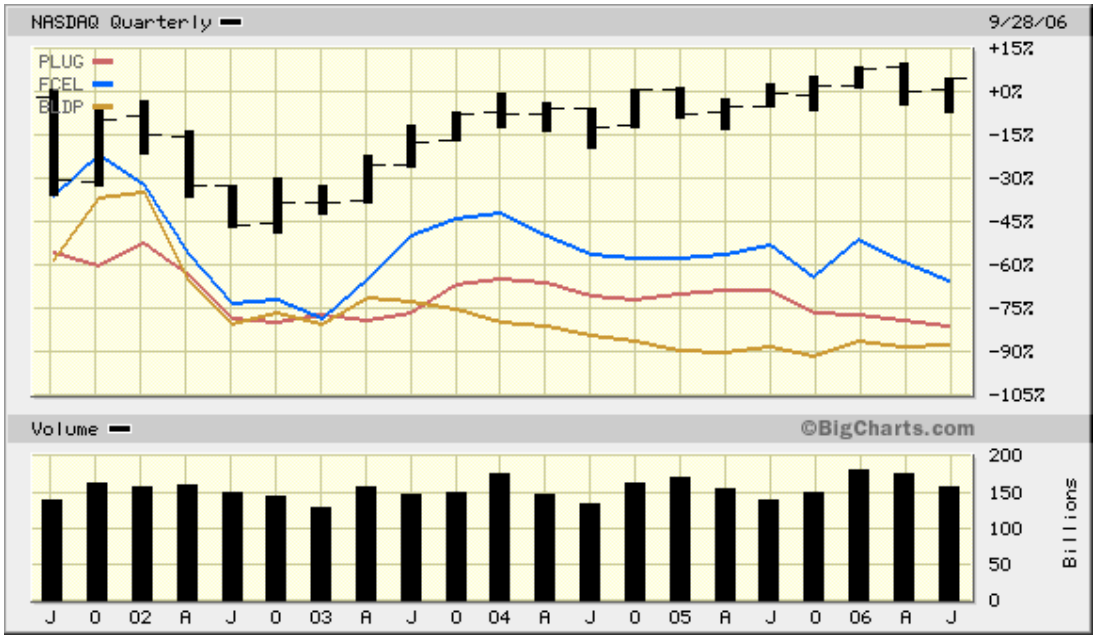
The market capitalization of publicly traded fuel cell companies witnessed significant changes over the five years when publicly traded fuel cell stocks had a dot.com like trading activity at the turn of the decade. The current market capitalization of the three major stationary fuel cell companies range from a low of $360M for Plug Power to a high of $654M for Ballard. More importantly, the share price-to-cash flow ratios are all negative with Ballard leading the way a -19.8 and FuelCell Energy with least unattractive value at -6.10. Clearly, the sizzle is out of the speculating on fuel cell stocks, and it is now incumbent for these companies to convince investors that they can produce a commercially viable product for a price, performance and warranty that the mid- and long-term market place demands.

Table 13 Market Profiles of Publicly Traded, Stationary Fuel Cell Companies

	Trading Symbol	Market Capitalization $M, 9/29/2006	Share Price – to – Cash Flow Ratio
Ballard	BLDP	654	-19.80
FuelCell Energy	FCEL	418	- 6.10
Plug Power	PLUG	360	- 7.20

Three major stationary fuel cell companies that are public traded were selected to portray the investment interest in fuel cells and their current operating profitability and cash flow. The three companies were Plug Power (PLUG) with a small scale stationary PEM fuel cell, FuelCell Energy (FCEL) with a .25 to 1 MW molten carbonate system and a 2-10 kW solid oxide system under development, and Ballard (BLDP) with their 1-3 kW stationary fuel cell system and one of the largest transportation fuel cell programs outside of the Big Five automotive companies. The Figure 1 graphic indicates that all three companies are trading between 65 to 88% below their stock prices five years earlier while the NASDAQ is trading about 5% above.

Figure 5 Past Five Years of Publicly Traded Stationary Fuel Cell Stocks (2001-2006)



6 Market Issues

6.1 Organizations Developing Propane Oriented Codes, Standards and Practices

The proposed support for the development of propane oriented, standards and practices for fuel cells was decided by PERC to not be pursued in this Phase of the contract. It was recommended that PERC or the National Propane Gas Association consider join the US Fuel Cell Council (USFCC)for $4,000 and directly participate in their update of the USFCC modifications to the LPG, Specifications and Test Methods Committee, but this recommendation was not acted upon. In June 2004, USFCC published the first ever "Literature Survey of Fuel Cell Contaminants," to serve as a ready-access data tool to the fuel cell industry and other interested groups. The report focuses upon the effects of contaminants on the performance and components of proton exchange membrane (PEM) fuel cells, including direct methanol fuel cells (DMFC), and components. The literature survey was conducted by the Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) for the US Fuel Cell Council Materials and Components Working Group. The report features a summary of sources of contamination for water, hardware, and gas reactants, followed by more than 115 tables summarizing the government and commercial literature surveyed.

Robert Wichert of the team did provide an overview of the present national and international standards setting efforts, and the synopsis appears Appendix 7. Also in the appendix is the colloquy between Larry Osgood on behalf of PERC and Robert Wichert on the primary findings from the US Fuel Cell Council has considered work to develop propane standards for fuel cell systems, more stringent than standards currently in place. Specifically the Power Generation Working Group has investigated propane standards that would restrict constituents as found in Table 14.

Table 14 US Fuel Cell Council's Proposed Propane Standards

LPG Constituent	Suggested Specification
C3H8	>90%
C3H6	<5%
C4H10	<1%
C4+	<0.1%
Balance	C2H6 or C3H8
CO2	<0.1%
COS	<100 ppbv
H2S	<100 ppbv
C2H5SH	25 to 35 ppmv

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6.2 State Incentive Programs to Accelerate Fuel Cell Commercialization

When the fuel cell technology matures, it will not enter a level field of play, particularly in the remote and rural applications. Competing technologies such as photovoltaics and small wind systems have, and will continue to have, significant financial, tax and regulatory incentives that will elevate their competitiveness with alternatives, including fuel cells using propane. Early commercialization of fuel cells will likely occur in those states that have the greatest financial, tax and regulatory incentives provided to an end-user, e.g. 34 states now have fuel cells eligible for net metering, up from just seven states two years ago. The team believes it is essential that PERC become cognizant of the incentives at the state level, and work to expand the eligibility of fuel cells wherever possible. The report provides herein to PERC the information necessary to allow PERC and its members to pursue these opportunities.

Federal funding for fuel cells largely supports research and development efforts for both stationary and automotive fuel cell applications, as well hydrogen infrastructure issues. State-level funding, on the other hand, tends to support the adoption of stationary fuel cells by end-users. A thorough knowledge and understanding of available state-level incentives may prove beneficial to those with an interest in the development and deployment of stationary fuel cells. Furthermore, stakeholders should be aware that there is a "long-standing tradition in American governance whereby states serve as laboratories for subsequent federal policy."

U.S. states offer a creative array of financial incentives to encourage the deployment of stationary fuel cells. These programs include industry recruitment incentives, corporate tax credits, net metering policies, grants, loan programs, rebate programs, personal tax credits, sales tax exemptions, property tax exemptions, and one production incentive.

It is important to recognize that most state-level financial incentive programs for which stationary fuel cells are eligible were not designed exclusively to support fuel cells. Rather, these programs typically are designed to promote the development and adoption of multiple renewable energy technologies. Many of these incentive programs also support wind, photovoltaics (PV), biomass, small-scale hydro, and/or other renewable energy systems.

Two state-level fuel cell incentive programs vanished in 2003—California's Public Leadership Solutions for Energy (PULSE), a loan program, and Massachusetts' Green School Initiative, a grant program—and a handful of programs were restructured, including grant programs in Illinois and Minnesota.

However, 10 new incentive programs were created during 2003 and early 2004:

1. Massachusetts - Fuel Cell Grants

2. New Jersey - Renewable Energy Advanced Power Program (a grant program)

3. New Jersey - Renewable Energy Economic Development (REED) Program (a grant program)

4. New Jersey - Reduced Energy Demand Options (REDO) for Local Governments and Schools (a loan program)

5. New Mexico – Clean Energy Grants Program

6. Pennsylvania - Energy Harvest Grant Program

7. New York - Solar and Fuel Cell Electric Generating Equipment Tax Credit

8. Louisiana - Net Metering policy

9. Maine - Renewable Resources Matching Fund Program (a grant program)

10. Wyoming - Renewable Energy Tax Exemption

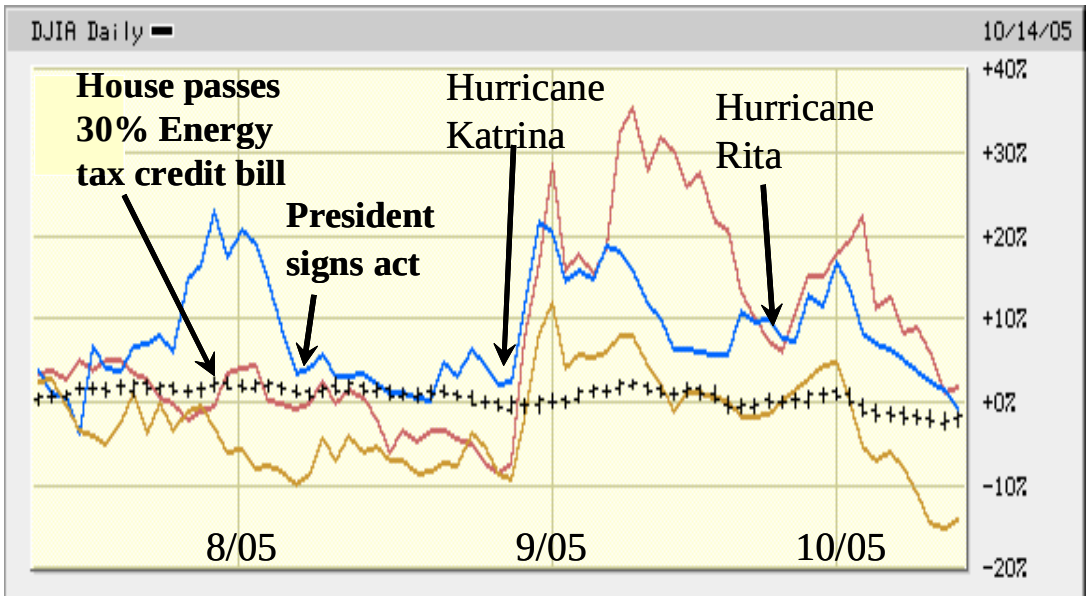
The net gain of state-level incentive programs is encouraging, especially considering the current dreary condition of dozens of state budgets. Stakeholders should be aware that a February 2004 report issued by the National Conference of State Legislatures warned that 31 states will have budget gaps totaling $35.6 billion for fiscal year 2005.

Another significant development in 2003 was the creation and evolution of the Public Fuel Cell Alliance (PFCA), a coalition of state, federal and international stationary fuel cell programs collaborating "to accelerate the widespread adoption and commercialization of stationary fuel cell technologies, fuel cell deployment and hydrogen infrastructure development in North America." The PFCA, which was still in the development process at the time of this writing, is supported by agencies in 21 states. Among other intentions, the PFCA proposes to facilitate joint projects among partners and serve as an information clearinghouse that will collect, standardize and publicize information pertaining to state, federal, and other fuel cell incentives and programs. The PFCA may be organized as a project of the Clean Energy States Alliance (CESA), a new nonprofit organization comprised of 17 state energy funds from 12 states. The CESA, managed by the Clean Energy Group, was established in January 2004.

Byron Washom's plenary session paper at the 2005 Fuel Cell Seminar was entitled "World Bank and US State Programs for Commercializing Fuel Cells". It was noted that the sum of the US State Incentive Programs exceed the US federal stationary fuel cell budget, and that clearly the emphasis must now shift to manufacturing capacity. The primary pre-commercial incentives by the states are oriented towards Production and Employment Retention Grants, Loans and Grants, Rebates, Price Incentives, Net Metering, Tax Incentives, Tax Exempt Financing, and Property Tax Exemptions.

Figure 6 contains an interesting chart of three publicly traded companies responding to technology push of the US House of Representatives passing to a 30% Energy Tax Credit up to $1000/kW (7/28/05) and President Bush signing the Energy Policy Act (8/8/05) coupled with the market pull for distributed generation as a result of a Category 4 Hurricane Katrina (8/29/05) and a Category 3 Hurricane Rita (9/24/05). The net result of these extremely favorable events for fuel cells was that the three publicly traded companies returned to their original trading ranges within 2.5 months of the first stimuli.

Figure 6 Trading Patterns on Three Fuel Cell Stocks After Significant Developments



6.3 R&D Opportunities in BOP Cost Reduction

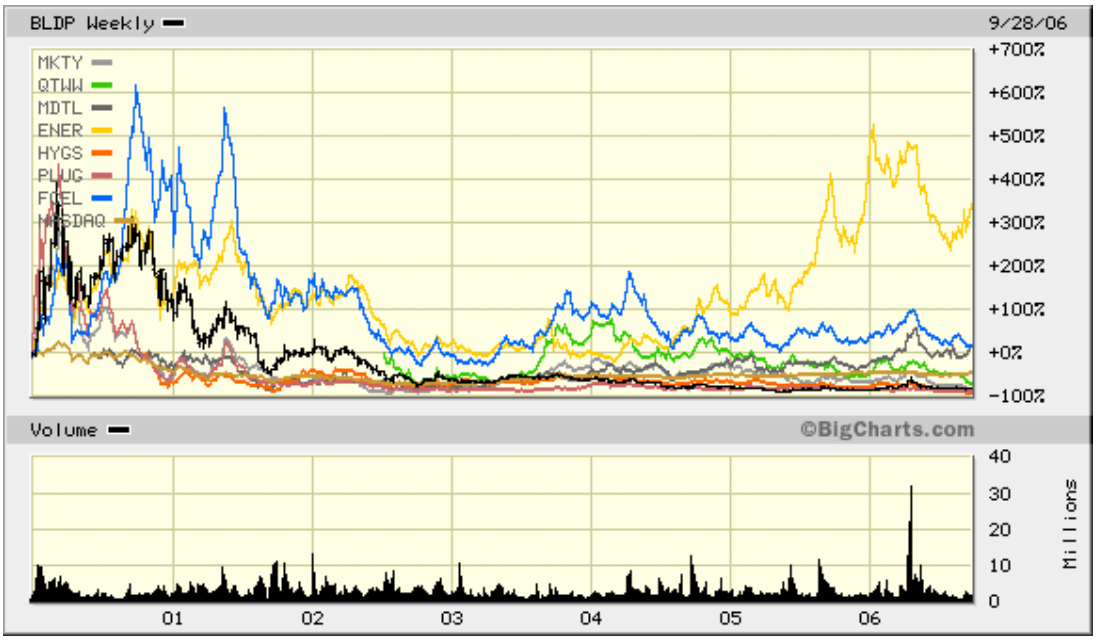
It was mutually agreed that the Balance of Plant (BOP) for small fuel cell systems typically represents 40-60% of the total installed cost of a fuel cell system. This fact has remained prevalent over the last five years, and the rate of cost of reductions in BOP has been slower than that in the fuel cell stack: thus, any gains in BOP will accelerate the rate of commercialization. Specific opportunities for the reduction in BOP did arise, Spencer Management reports herein potential co-funding or receiving the research results on a timely basis. The primary opportunities are with the inverter, monitoring, start-up/shut down control logics, and fuel processors for the Core Technologies Program under the DOE SECA program, and the best contact is Mr. Donald Collins at the National Energy Technology Laboratory (NETL) in Morgantown WV. His contact information is 304-285-4156 and wayne.surdoval@netl.doe.gov

6.4 Assessment of Timing for Commercialization of Propane Based Market Segments

Provide a realistic assessment of the market potential for propane-powered fuel cells. Determine installed-cost levels compared to electricity costs that must be obtained to commercialize propane fuel cells and compare to the current levels. Report the applications that are most likely to be commercialized first and who will be the customers. Report the realistic time to commercialize fuel cells in general and for propane specifically. This is to be broken down per application (i.e. recreational vehicles, commercial, residential, etc.).

"Managing expectations" has become the new mantra of the fuel cell industry following the hyper active investor interests over the last six years. The past six years of the past inflated periods and the current stagnant periods are seen in Figure 7 attests to the fact that the bloom is off the rose with respect to investor interests given that the technology is emerging slower than forecasted and is more costly than alternatives sources.

Figure 7 Past Six Years of Publicly Traded Fuel Cell Stocks (2000-2005)



Legend of trading symbols: Mechanical Technology Inc (MKTY), Quantum Fuel Cell Systems Worldwide (QTWW), Medis Technologies Limited (MDTL), Energy Conversion Devices (ENER), Hydrogenics Corp (HYGS), Plug Power (PLUG), Fuel Cell Energy (FCEL), Ballard (BLDP).

The sizes of the propane oriented fuel cell markets will be developed using the well established terminology of "Moore's Product Life Cycle": Innovators, Early Adopters, Early Majority, Late Majority, and Laggards. Forecasting the timing, sequencing and size of the various markets for fuel cell applications is a process highly influenced by R&D and available "early adopter's" incentives. Generally speaking, the timing to commercialization will be substantially slower and the size will be smaller than any previously published forecast. The pivotal issue for propane oriented companies is the absolute success of demonstrating propane reforming that meets the specifications of the sulfur intolerant PEM fuel cell stacks. Until that reforming technology is developed at a competitive cost, the greater promise may rest with the longer term solid oxide fuel program sponsored by DOE.

The Japanese residential market using LPG will represent a significant bellwether for the US markets with respect to price points and technical performance of fuel cells systems for the 2004-2008 timeframe.

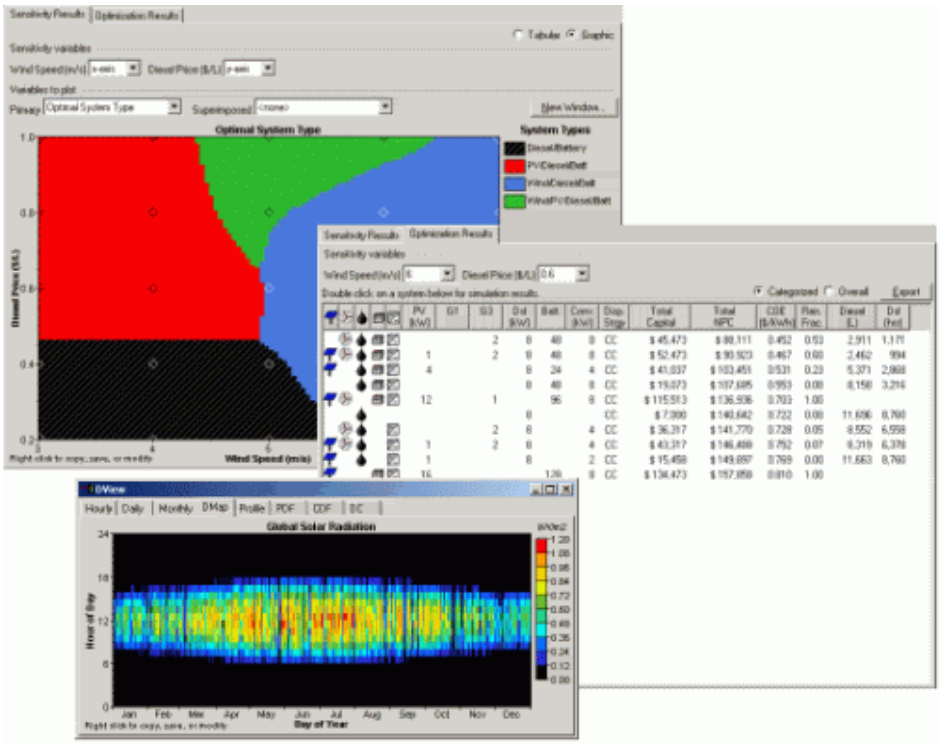
Setting an appropriate "target" price for propane technology for the US markets is necessary to ensure successful commercialization, and this price is different from the initial "introduction" price that gets the technology accepted by the Innovators and Early Adopters. For example, DOE has set the cost goals of fuel cell RV APU's at $1500/kW and $400/kW in 2006 and 2010, respectively. The fuel processor cost allocation would typically be approximately 10-15% of these goals.

6.5 Validated Model for Competitive Price Assessments in DG Applications

The team provided guidance for PERC to download a validated model HOMER for the National Renewable Energy Laboratory (NREL) that conducts competitive price assessment that simplifies the evaluations of design options for off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. HOMER's optimization and sensitivity analysis algorithms permit an end user to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. HOMER models both conventional, renewable energy and fuel cell technologies. Figure 8 is one of graphical views of the results. The schematic displays the components that the model will simulate and allows an analyst to quickly access technical and economic data for each component. Load, Component and Resource windows are where the analyst enters, imports, or synthesizes information about electric demand, component capacity and costs, and resource availability.

Spencer Management reviewed the features of this model with respect to recommending it to PERC members, and strongly endorses the model for any detailed analysis that they may wish to undertake in the future.

Figure 8 Representative Output on Optimization Model



6.6 Assessment and Strategies for RV and Mobile Applications

Assess the potential for using propane fuel cells in recreational vehicles and other mobile applications. Determine if current reformer and stack technology is robust and durable enough for mobile applications. If not, report what development strategies might improve

robustness and durability, and estimate how long such development might take and what it might cost.

Another fuel cell system market of importance and direct interest to PERC is that of Auxiliary Power Units (APU) and/or remote/portable power applications for fuel cells that are receiving increased attention as early fuel cell markets. Some of these APU and remote/portable power applications are ideally suited for propane use in the fuel cell system. These applications are those where either propane is already widely used and accepted by consumers (e.g., recreational vehicles, remote power) or where the propane fueling system (fuel and fuel processor) can exhibit significant energy density or cost benefits compared to other energy sources (e.g., compressed hydrogen). The DOE specifications are presented in Table 15.

Table 15 DOE Specifications for Recreational Vehicles' APUs (3-5 kW avg., 5-10 kWp)

	Parameter	Units	2003[1]	2006	2010
Complete System including BOP	Specific Power	W/kg	50[2]	80	120
	Power Density	W/L	50[2]	80	120
	Efficiency @ Rated Power	% LHV	20	25	35
	Cost	$/kW	>2,000	1,500	400
	Cycle Capability (from cold start) over operating lifetime	Number of cycles	10	20	500
	Durability (operating life)	hours	100	1,000	5,000[3]
	Start-Up Time	minutes	2-3 hours	30-45	15-30

(1) Estimate of current capability based on cell and small stack laboratory developments.
(2) Without power conditioning.
(3) Durability for light-duty vehicles is 5,000 hours and 15,000 hours for heavy-duty vehicles; the 15,000 hour durability for heavy-duty vehicles is targeted for 2015.

One leveraging opportunity with DOE included development, construction, and validation of fuel cell power systems for APU applications. This scope included a very relevant power range of 3-5 kW average/5-10 kW peak for APUs for recreational vehicles and a less relevant 10-30 kW for refrigeration for long-haul trucks. The RFP required that the technology to operate on hydrogen or hydrogen derived from on-board processing of propane or low-sulfur diesel fuel, depending on the application and type of fuel cell. DOE funded proposals with Cummins Power Group and Delphi to provide for up to three (3) multi-year, cost-shared projects with durations of 3 years and government funding of approximately $3 million for each project. The specific tasks of the DOE program are presented in Appendix 3 on page 70.

The first selected contractor selected was Delphi of Troy Michigan. The DOE's Office of Energy Efficiency and Renewable Energy and Delphi will share the cost of the 3-year, $4.75 million project. Delphi will lead the technical development, working with subcontractor team member Volvo Trucks North America, Inc. and other OEM customers to be announced at a later date. According to DOE estimates, 840 million gallons of diesel fuel are consumed each year by the idling of 480,000 long-haul trucks, resulting in emissions of 20 billion pounds of carbon dioxide into the atmosphere each year. It further generates air-polluting emissions of 100 million pounds of nitrogen oxides and 4 million pounds of particulates. Delphi's SOFC APU can reduce the fuel usage and the corresponding emissions during idling by as much as 90 percent, according to DOE estimates. The system will allow truck owners to power air

conditioning, heater, TV, radio, computer and other electronic devices during the drivers' rest periods without having to keep their engines running.

In Phase One, Delphi will work with Volvo Trucks North America to define the application requirements, including the load profile that Delphi will use to simulate fuel economy improvement. Phase Two will focus on the full system design and SOFC APU component build, development and test. Phase Three will integrate the sub-system components at the system level to validate a fully integrated system design. Fuel efficiency improvements will be confirmed by exposing the SOFC APU to simulated application conditions for commercial trucks. The Delphi team has enlisted an advanced transportation technology consortium, Electricore, Inc., to serve as administrative program manager for the project. Delphi currently estimates the technology will be available in the market sometime between 2008-10.

In a paper presented at the 2005 Fuel Cell Seminar revealed the Delphi system development to date can report,

> Delphi has successfully completed the system integration of a Stationary Power Unit comprised of methane CPOx reformer, 2 x 30-cell Gen 3 stacks, electronic controller and control software, power electronics, and BOP components. The system is a complete SOFC system capable of automatic cold-start-to-run operation and internal 42 VDC and 12 VDC power bus support. The system has direct DC output, with an optional AC inverter employed for AC electrical loads. This system was designed to support up to 3 kW net electrical output at 18% efficiency, with future upgrades allowing up to 35% efficiency.

A paper presented at the 2005 Fuel Cell Seminar by James Butcher of Cummins Power Group indicated that their SOFC APU for a Class 7/ Class 8 Truck has pursued a diesel based, fuel cell rather than propane due to previous market rejection on a second source of fuels by both fleet and independent owners. Due to difficulty and challenges with respect to start time, ramp rate (ability to increase output to support additional load) and impact on storage battery size and life, control strategy, fuel reformation and water control, shock an and vibration Isolation, durability in real world mobile applications, and total system cost, PERC can anticipate a longer than anticipated R&D schedule in this diesel based APU program. The transition to propane APU fuel cells at the RV and long haul truck markets would presumably follow the diesel program. Butcher also noted that,

> The limited success of today’s APU’s in the line haul truck market can be directly attributed to the failure of these products to address the critical combination of function and cost necessary to earn their way in the highly competitive trucking industry. Today’s truck owners are looking for a payback on their investment of less than 18 months, and with high installation costs and historically lower fuel prices, the equation has not balanced.

In a November 28, 2005 email to Spencer Management Associates in support of this PERC report, Dan Norrick of CPG noted that,

> CPG began our SECA program focused on LPG as a fuel that could potentially be acceptable to the RV market for use in fuel cells. It was less of a challenge to reform, and was being carried on RV's. We shifted our SECA focus to natural gas in response to DOE's direction to test on natural gas, and have

> shifted our longer range focus to diesel based on progress we see with diesel reforming and the desire for many mobile applications to run on diesel fuel. We recognize that longer term it is probable that we will want to operate on all three fuels (diesel, LPG, natural gas) to cover all the potential applications, but diesel will be a key fuel to support the quickest market acceptance.

Therefore, it does not appear that Cummins Power Group will represent a modest near term collaboration opportunity; however, the exceptional forthright discussion of the technical and market challenges to on-board, truck long haul fuel cell APUs should be closely studied for any potential APU co-funding.

7 Global Propane Oriented Fuel Cell Initiatives

7.1 Assessment of Global, Propane Fuel Cell Demonstrations

The team investigated and reported on propane fuel cell installations that have occurred without PERC funding throughout the world. Such installations include, but are not limited to, those sponsored by the U.S. Department of Defense, the European Commission, the U.S. Department of Energy, NEDO and NEF of Japan, the fuel cell industry (e.g., Plug Power, IdaTech, UTC Fuel Cells), and others.

The U.S. Army Corps of Engineers (ERDC-CERL) has conducted fuel cell research, development and demonstration programs for more than 16 years. In October 2005, Robins Air Force Base received ten Plug Power 5kW fuel cells as part of the Robins Micro-grid Project. The fuel cells will provide 275,000 kilowatt hours of power to the base's power source until their departure in October 2006, and they will reform propane gas and extract hydrogen. Previously ERDC-CERL had reported that earlier Plug Power units had achieved an average overall efficiency of 45.70%, with an average electrical efficiency of 24.10% and an average thermal efficiency of 21.58%, based on the Lower Heating Value (LHV) for propane.

As previously emphasized, the real focus for demonstration plans and results should be on Japan. The team will gather information and report on any relevancy with Japan's New Energy Foundation (NEF) which aims to install 1 – 5 kW demonstration units at 31 residential and commercial premises in Japan in 2003-4. Thus units will be fuelled by city gas, LPG, kerosene and naphtha. Partners include Ebara Ballard, Hitachi Home&Life Solutions, Ishikawajima-Harima Heavy Industries, Kurita Water Industries, Marubeni, Matushita Electrical Industrial, Mitsuhishi Heavy Industries, Nippon Oil, Sanyo Electric, Toshiba and Toyota Motor. Additionally, the Liquefied Petroleum Gas Center is to develop LPG fueled PEFC. The targets are to develop reformer for LPG and 1 kW PEFC cogeneration system technology for domestic use to be practical level which results in 80% in total efficiency. The participants are Nippon Oil, Mitsubishi Corporation, Idemitsu Kosan Co., Ltd., Matsushita Electric Industrial Co., Ltd., Air-Water Inc. and Iwatani International Corporation, and the duration is 5 years and the budget is US$17.5M with a 66% subsidy.

Of particular interest will be Nippon Oil's rare public announcement that in April 2003 they will commence monitoring tests on around 100 units of home-use fuel cells nationwide. LPG will be the fuel source used to produce hydrogen. Nippon Oil stated that they chose LPG as the fuel since Japan is a land of mountains and slopes, less than 5% of the nation's surface is suitable for laying gas pipelines. This limitation makes for a peculiar situation in Japan comparison with the United States or Europe. For that reason, they chose LPG as the most appropriate fuel source for creating hydrogen, since it can be transported anywhere in the country. Nippon Oil also believes in the principle of "producing at home the energy we use at home." Thus, the Nippon Oil project could represent the largest, nearest term propane-oriented fuel cell demonstration program in the world.

Extracting data on a timely basis from the Japanese is always problematic, but the team will draw upon its resources at the World Bank, the Japanese members in NFCRC, and our ongoing relationship with the Fuel Cell Development Information Center of Japan (FCDIC). Spencer Management presently possesses and maintains a log of all LPG fuel cell oriented press releases from Japan for the past two years.

7.2 Global RD&D Fuel Cell Funding Allocations

Report the areas that the majority of government and private funding is being allocated and is planned to be allocated.

At the present time, the US Department of Energy, the New Energy Foundation and NEDO of Japan, the European Union through their Framework 4 through 7 programs and the Canadian Government are the four largest sources of publicly funded fuel cell research, development and demonstration (RD&D) for stationary and transportation applications. At the state level in the US, the majority of support comes from incentives and demonstration programs. Due to the differences in terminology, cost sharing accounting and appropriation procedures, it is extremely difficult to aggregate these four different public funders into one aggregate and accurate table. Therefore, Spencer Management proposes to present the funding plans of each of the four government programs and comment on the general trends, particularly with respect to propane as a feedstock.

The unprecedented interest by the G8, World Bank and Asia Pacific Partnership, as well as the US and Japanese public and private sector, in small stationary fuel cells that have a potential to depend upon propane as the primary opportunity fuel for the residential, remote and back up power markets. Ample evidence is available that a large set of market launching orders will most likely occur initially in the developing economies superseding that of the industrialized nations. Thus, the industrialized nations will probably have greater access to the lower cost, more mature subsequent generation of propane fuel cells.

The Japanese and North American fuel cell companies now realize that the existing market aggregation and supply infrastructure of the propane industry in the residential markets not served by the local electric utility distribution companies represents an indispensable springboard to the larger, longer term market. However, propane will not likely be used to any significant degree in fuel cell transportation applications of the future.

The team spent a modest effort to report in a macro sense on the areas that the majority of government and private funding is being allocated and is planned to be allocated. In a paper at the 2005 Fuel Cell Seminar, David Jolie, the Editor of Fuel Cell Today, presented the below estimates of the funding by the major central governments. Figure 2 indicates a total level of effort of US$760M/yr with Japan being the largest single funding source at $310M. It is estimated that the private sector is placing at least an equal amount into fuel cell R&D, and the state governments within the US have provided at least DOE's total of $190M in fuel cell incentives.

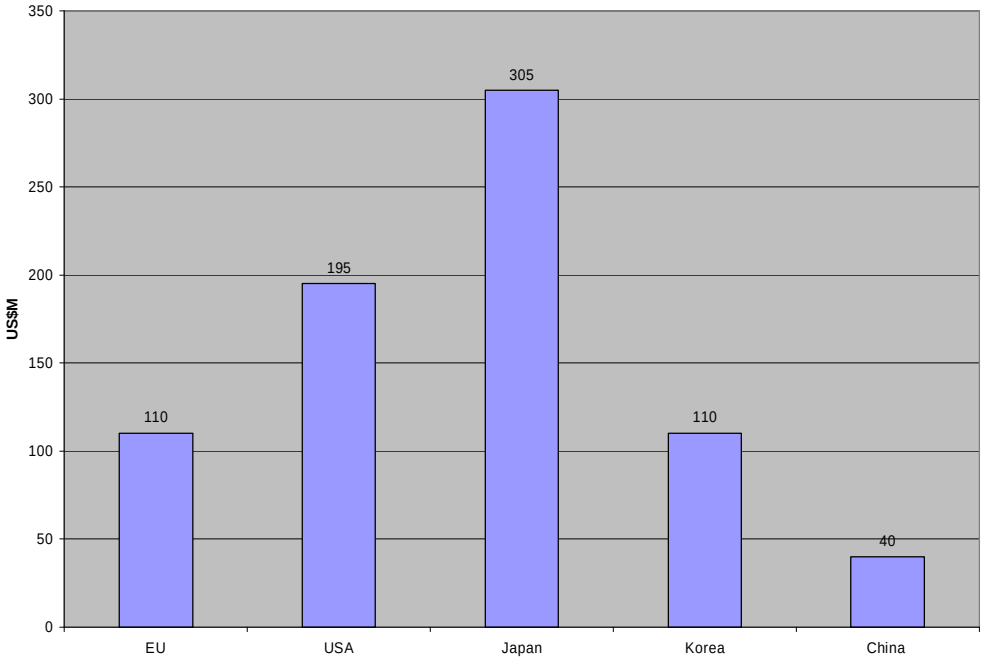



Figure 9 Estimated Funding for Fuel Cells by Central Governments