"Phase I Feasibility Study of an Integrated Hydrogen PEM Fuel Cell System"

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Final Report

FCR-14857

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Prepared for

**U. S. Department of Energy
Golden Field Office
1617 Cole Boulevard
Golden CO 80401**

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Draft Final Report

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1.0 INTRODUCTION and SUMMARY

This report is was completed under Department of Energy Contract No. DE-FC36-97GO10214 by International Fuel Cells (IFC) and a team from W. L. Gore & Associates and Sandia National Laboratory. Evaluated in the report is the use of hydrogen fueled proton exchange membrane (PEM) fuel cells for devices requiring less than 15 kW. Metal hydrides were specifically analyzed as a method of storing hydrogen. There is a business and technical part to the study that were developed with feedback from each other. The business potential of a small PEM product is reviewed by examining the markets, projected sales, and required investment. The major technical and cost hurdles to a product are also reviewed including: the membrane and electrode assembly (M&EA), water transport plate (WTP), and the metal hydrides.

IFC concluded that the best potential stationary market for hydrogen PEM fuel cell less than 15 kW is for backup power use in telecommunications applications. This market is highly concentrated and requires advanced power systems to enable enhanced reliability of our nation's communication infrastructure. Fuel cells offer many of the benefits required in this application. The conservative financial projections indicate that beginning a business today with a focus on fuel cells for telecommunications will produce a self-sustaining business that achieves an internal rate of return (IRR) of 9 percent, below the investment threshold. This section has followed the basic format of Bizplan, a product developed by Jian Inc., to facilitate the creation of a business plan. However, because of the early stage of product development, several portions of Bizplan have not been included.

The telecommunications market is characterized by a concentrated customer base with expanding need for reliable distributed backup power. While many different product sizes may be possible, it was determined that a 10 kW fuel cell with 24 hours of hydrogen storage would have the largest initial market potential. The performance characteristics of fuel cells, such as low maintenance, rapid start-up, and dc power output match the requirements of the application. Also, since the application is of a stationary nature, the weight associated with metal hydride hydrogen storage is less of an issue. However, working together with Gore and Sandia, it was determined that while an integrated hydrogen PEM system for telecommunications is technologically feasible today, it could not be built and sold in the acceptable price range of \$1,500 to \$2,000 per kilowatt, including the hydrogen storage without additional technical advancements. Of all the components of the system, the cost of the metal hydrides appears to be the most cost prohibitive. In addition, the infrastructure issues regarding the cost effective filling of distributed hydrogen containers has yet to be resolved and requires further attention by the Department of Energy. The business plan addresses these issues and proposes a plan for meeting this challenge. To be investable, this plan requires a method of reducing capital costs.

The technical portion of the report addresses the performance and cost issues with the major components of an integrated PEM system. For water transport plates, also known as separator plates, the issue is to reduce the cost of the plates while maintaining its porosity, electrical resistivity, hydrophilic nature, and its strength. IFC and Sandia worked together to new methods of manufacturing that appeared promising in reducing costs but some issues regarding the conductivity and strength require additional development. As for the M&EA, IFC and Gore evaluated several different combinations of catalysts and electrodes and determined that reduced costs are achievable without reducing performance. IFC and Sandia evaluated both a high temperature and low temperature hydride for possible use in a 10 kW long running devise. While the high temperature hydride had superior performance, the lower temperature hydride meets the needs of telecommunications applications at a lower cost. In addition, the high temperature hydride would require supplemental heating.

2.0 BUSINESS PLAN FOR HYDROGEN PEM POWER PLANT

This Business Plan follows the suggested format of Bizplan but has several additions and subtractions that adapt the Bizplan model to early stage technology businesses. The business plan specifically addresses an integrated hydrogen PEM power plant for telecommunications applications.

2.1. Executive Summary

2.1.1. Vision/Mission

International Fuel Cells Corporation (IFC) is a corporate venture of United Technologies Corporation and Toshiba Corporation and is part of the Hamilton Standard division of UTC. The business was formed in 1985. IFC is dedicated to providing world class fuel cell products that provide clean, quiet, efficient power generation. As we leverage our experience and history, we will continue to create world-class products to meet customer demands in the following areas:

- Efficient reliable power plants for defense and space applications.
- Clean, efficient stationary and backup power plants.
- Power plants for transportation applications.
- Power plants for portable power.
- On-site synthesis gas generation for industrial applications.

2.1.2. Background

International Fuel Cells continues to be the only company in the world that offers fuel cell power plants on a commercial basis with scheduled delivery dates and a warranty.

IFC employs approximately 400 people. Over 60 percent of the professional staff has at least 20 years of experience in the technologies used in fuel cell power plants. IFC, and its predecessors at UTC, has designed and delivered 18 different models of fuel cell power plants. IFC has delivered nearly 400 power plants that have accumulated 2 million hours of operating time.

2.1.3. Objectives

International Fuel Cells' objective is to commercialize fuel cell related technologies. To achieve this objective IFC will leverage experience with one or two basic technology platforms to provide multiple products to customers. One of these technology platforms will be water-cooled PEM power plants. Utilizing water-cooled PEM, IFC will develop products ranging from transportation applications, such as automotive, to stationary power plants ranging in size from 10 kW to 300 kW. The first products within this platform may potentially be fueled by pure hydrogen. In later years, products operating on hydrocarbon reformat will be introduced. The product launching of a 10 kW hydrogen fueled fuel cell for backup power in telecommunications is being evaluated. Additional product launching will follow specific market demands.

2.1.4. Capital Requirements

According to the opportunities and requirements for fuel cells for telecommunications described in this business plan, and based on what we feel are sound business assumptions, our total capital requirements to launch the new product are \$15 million through the fifth year. Capital requirements will be utilized for the following activities:

- Design: Design integrated product for telecommunications including fuel cell stack, hydride hydrogen storage, and electronics.
- Technology: Advanced technology development for membranes, water transport plates, and hydrides to reduce costs and improve manufacturability.
- Manufacturing: Build manufacturing facilities in a modular fashion to produce thousands of units by the fifth year.

- Testing: Test advanced materials, and build and test alpha and beta units.
- Marketing: Develop in-depth profile of customer needs to support product design. Develop sales and marketing plan including distribution network and product literature

2.1.5. Management Team

IFC management team is led by senior managers with diverse business experience inside and outside the fuel cell industry. The President of International Fuel Cells is Mr. Robert Suttmitter, who has more than 30 years of experience with United Technologies' affiliated companies. Before joining IFC, Mr. Suttmitter was president of Dow/UTC a joint venture company. IFC's vice president for business development is Mr. William Hahn. Mr. Hahn has nearly 30 years of experience with UTC and most recently was in charge of business development with Hamilton Standard. In addition, IFC's management team consists of individuals with expertise in marketing, finance, engineering, and design.

In-House Management:

Mr. Robert Suttmitter	President
Mr. William Hahn	Vice President for Business Development
Mr. Gordon Sigman	Marketing
Mr. Leonard Bonville	Vice President of Engineering
Mr. Eugene Hall,	Vice President of Manufacturing
Ms. Martha Leonard	Chief Financial Officer
Ms. Lynn Banis	Corporate Attorney

In addition, management and financial support are provided by Hamilton Standard, IFC's corporate parent.

2.1.6. Product Strategy

The introduction of a 10 kW fuel cell for telecommunications is part of an integrated product strategy that leverages IFC's current experience in the fuel cell market and will develop into a family of products with similar technological needs. Through its ONSI Corporation subsidiary, IFC sells the 200 kW PC25™ fuel cell power plant for commercial buildings. Through the experience of installing and operating of the PC25 for customers with a demand for high quality electricity, IFC has identified a need for smaller fuel cells with 10 kW of power.

One market in particular is telecommunications. It has a demand for 10 kW of dc power for radio frequency repeater stations, digital repeating stations, and cellular towers. The major telecommunications companies, such as ATT and the Bell companies are unhappy with the performance and reliability of the power systems currently available. The primary issues are the degradation of battery backup systems over time and the unreliability of diesel. Telecommunications companies are actively seeking alternative solutions to their power needs. IFC's technology can serve this market of existing customers and contacts immediately by providing emergency backup systems fueled by stored hydrogen. This product would be based on water-cooled PEM technology because of its favorable operating characteristics in the 10 kW range. This technology platform, which IFC is developing for automotive applications, will become the base for multiple product offerings. The first products within this platform may be fueled by pure hydrogen (telecommunications and transportation). In later years, products operating on hydrocarbon reformat will be introduced. Additional product launching will follow specific market demands. Ultimately, IFC products will be able to provide power to remote villages, an opportunity IFC has identified with significant business opportunity as well as a social benefit.

2.1.7. Research and Development

IFC has a research and development base in the technologies that enable fuel cell products. These include the design of basic fuel cell components and processes, such as catalysts, catalyst support, flow plates, controls and electronics for PEM, phosphoric acid, and alkaline electrolyte systems. In addition, IFC continues to expand its fuel processing capability for fuel cell power plants and for the industrial hydrogen market. IFC works closely with vendors of supporting technologies, such as electronics, to provide products that are fully integrated.

2.1.8. Market Definition

The telecommunications market targeted by IFC consists of dc powered switching or transmission equipment located in a distributed network around population centers. These facilities are traditionally outfitted with 4 to 36 hours of battery back up and possibly with backup diesel generators for longer duration outages. The market can be divided into five distinct sets of customer products that need power supply and power assurance. The segments are:

- Fiber optic repeating stations (Central offices)
- Fiber optic multiplexing stations (nodes)
- Cellular towers
- Remote repeating telecommunications
- Internet backbone computing facilities

Within each segment, there is a requirement for both primary power and backup power. IFC's initial market segment target would be the supply of equipment to provide backup power to cellular towers. Backup power for the other types of facilities would follow. According to Personal Communication Industry Association, and estimates from Bell Atlantic and SNET, up to 700,000 telecommunications facilities will be installed in the US over the next 20 years that will require backup power. IFC estimates annual sales of 10 kW fuel cell telecom units could reach 2,000 units at a cost of \$15,000 per unit in the year 2003 if this business plan is implemented. In this year, the estimated revenue from this product will reach \$30 million.

2.1.9. Competition

Initial competition in this market will come from conventional battery and diesel generators. While operators are unhappy with conventional solutions to their needs, the limitations of these systems are understood. The introduction of new technologies will require extensive testing and demonstrations. There are no existing fuel cell products that meet this market. It can be expected that Ballard Power Systems, H-Power, and Plug Power would introduce fuel cell products in the future. IFC's strategy is to be first to market fuel cell systems in this segment to secure the strongest partners and gain the confidence of system operators.

2.1.10. Risk

The greatest risk of initial product launch of a hydrogen fueled backup power systems is the implementation of a refueling strategy that meets the needs of the customer to reduce the time and expense of maintaining a network of distributed backup systems.

2.1.11. Marketing Plan

Response from existing customers, market research, and unsolicited inquiries indicates a strong need for new methods to backup distributed systems. Our proposed system will deliver equal reliability and capital costs of battery systems with significantly lower maintenance costs.

IFC's marketing plan starts by working with the leading equipment providers, such as Lucent Technologies, and the major potential customers, such as Bell Atlantic, to ensure our backup system

meets the needs of the market. Our ultimate aim would be to completely replace current methods for backup power for telecommunications and eventually provide primary power. IFC will have extensive beta testing of units in the field prior to full product launch. At this time we anticipate product launch in the year 2001 is achievable.

IFC's marketing strategy incorporates plans to sell our power system through existing equipment suppliers to the telecommunications industry. Two international providers of equipment with whom IFC regularly discussed power issues are Lucent Technologies and Bellcore. In addition, preliminary discussions are underway with New Power Associates in New Jersey and Hutton Communications in Pennsylvania.

2.1.12. Financial Plan

The attached financial plan shows preliminary revenue projections, operating expenses, and capital requirements. It is expected that a business focused on the telecom market would lose money for the first 4 years of operation. These losses would total nearly \$15 million before the product line began to earn a profit in the sixth year of operation. The net income after taxes is expected to be \$2.7 million in the sixth year and each of the following years when sales are expected to reach 2,000 units. The IRR for the net income after taxes for ten years is calculated to be 9 percent, below investment threshold. Thus, using the assumptions in this business plan, investment in a telecom is not financially justified without assistance in reducing development and capital expenditures.

2.1.13. Conclusion

Through our market investigations, we have concluded that there is a market for a fuel cell product for backup power in telecommunications. Although not evaluated in this business plan, we believe the product would have substantial export opportunity. However, the financial projections indicate that beginning a business today with a focus on fuel cells for telecommunications will not produce a self-sustaining business that achieves an acceptable internal rate of return (IRR). Therefore, this business activity must be supported by one or more outside sources to make it a viable business. One of these sources may be the Department of Energy to support the substantial development activity that is required to reduce the cost of critical parts of the power plant. A second source of activity would be to leverage activities with related products, such as fuel cells for transportation, to utilize technology advances in one area for application in another. IFC intends to have some of these synergies available in the future.

For the next phase of activity, attention should be focused on solving some of the advanced technology issues concerning PEM fuel cells and hydrogen storage. Reducing cost, weight, and volume are primary concerns. In addition, devising strategies that will allow a system to operate in severe climatic conditions is important to the application of an integrated PEM system in remote locations that need power, such as Alaska. Finally, the Department of Energy must focus resources on enabling a hydrogen infrastructure to develop.

2.2. Company Overview

2.2.1. Legal Business Description

International Fuel Cells Corporation is incorporated in the state of Maryland. IFC's office and manufacturing facilities are located at:

195 Governor's Highway
South Windsor, CT 06074
860-727-2200

2.2.2. Management Team

IFC management team is led by senior managers with diverse business experience inside and outside the fuel cell industry. The President of International Fuel Cells is Mr. Robert Suttmiller, who has more than 30 years of experience with United Technologies' affiliated companies. Before joining IFC, Mr. Suttmiller was president of Dow/UTC a joint venture company. IFC's vice president for business development is Mr. William Hahn. Mr. Hahn has nearly 30 years of experience with UTC and most recently was in charge of business development with the Hamilton Standard division of UTC. In addition, IFC's management team consists of individuals with expertise in marketing, finance, engineering, and design.

The senior leadership team includes:

Mr. Robert Suttmiller	President
Mr. William Hahn	Vice President for Business Development
Mr. Gordon Sigman	Marketing
Mr. Leonard Bonville	Vice President of Engineering
Mr. Eugene Hall	Vice President of Manufacturing
Ms. Martha Leonard	Chief Financial Officer
Ms. Lynn Banis	Corporate Attorney

2.2.3. Board of Directors

International Fuel Cells board of director's includes:

Mr. Raymond Kurlak (Chairman)	President, Hamilton Standard Corporation
Mr. Thomas Rogan	Vice President Finance & Administration Hamilton Standard Corporation
Mr. Tetushi Matsushita	Chief Technology Executive, Energy System Group Toshiba Corporation
Mr. Robert Suttmiller	President, International Fuel Cells
Mr. Eugene W. Hall	Vice President Operations, International Fuel Cells

2.2.4. Staffing

IFC employs approximately 400 people. Approximately half of these employees are professional staff. Approximately 60 percent of these employees have at least 20 years of experience in the technologies used in fuel cell power plants. To complete this project business plan, IFC will need to expand its staff to include additional skills and manpower in marketing, engineering, and especially in manufacturing. The exact number of employees required has not been determined.

2.2.5. Joint Development Efforts

International Fuel Cells has existing agreements with Toshiba Corporation and Ansaldo Corporation to market fuel cell power plants. Given the proper business environment IFC would anticipate expanding these relationships to include telecommunications fuel cells. In addition, IFC would pursue agreements with other major suppliers to the telecommunications industry, such as Lucent Technologies, Northern Telecom, and Motorola.

2.3. Product Strategy

2.3.1. Current Product

The introduction of a 10 kW fuel cell for telecommunications is part of an integrated product strategy that leverages IFC's current experience in the fuel cell market and will develop into a family of products with similar technological requirements. Through its ONSI Corporation subsidiary, IFC sells the 200 kW PC25™ fuel cell power plant for commercial building applications. The PC25 is the only fuel cell power plant available with a commercial warranty and certified by the American Gas

Association (Figure 2-1). Over 150 PC25s have been produced with some units operating in the field for more than 5 years.

Figure 2-1. AGA Certification for PC25[™] Power Plant

Through the experience of installation and operation of the PC25 for customers with a demand for high quality electricity, IFC has identified a need for smaller fuel cells with 10kW of power. With this level of power, there is a multitude of market demands that can be met. One market in particular is telecommunications. It has a demand for 10 kW of dc power for radio frequency repeater stations, digital repeating stations, and cellular towers.

Major telecommunications companies, such as ATT and the Bell companies are unhappy with the performance of and reliability of the power systems currently available to them. The primary issues are the degradation of battery backup systems over time and the unreliability of diesel engines. Telecommunications companies are actively seeking alternative solutions to their power needs.¹ IFC's technology can serve this market of existing customers and contacts by providing emergency backup systems fueled by stored hydrogen.

¹ Distributed Premium Quality Power: Meeting the Needs of the Emerging High-Density Communications Network. A White Paper Prepared by Lucent Technologies, EPRI, Amoco/Enron Solar, GPU Energy, The Pennsylvania State University, Princeton University.

This product would be based on water-cooled PEM technology because of its favorable operating characteristics in the 10 kW range. This technology platform, which IFC is developing for automotive applications, will become the base for multiple product offerings. The first products within this platform will be fueled by pure hydrogen (telecommunications and transportation). In later years, products operating on hydrocarbon reformat will be introduced. Additional product launching will follow specific market demands. Ultimately, IFC products will be able to operate on petroleum fuels and provide power to remote villages, an opportunity IFC has identified that has significant social benefit.

In addition to the fuel cell, a complete system will include hydrogen storage, a power conditioner, and an energy storage unit to provide 10 seconds of power until the fuel cell is fully functional. The hydrogen storage will be provided by metal hydrides developed by Sandia Laboratories and licensed by an independent company for manufacturing. Energy Conversion Devices has expressed an interest in working with Sandia and IFC in developing this product. The power conditioner and energy storage unit, which may be a super capacitor or a flywheel, have not yet been identified.

2.3.2. Proprietary Technology

International Fuel Cells products are protected by nearly 200 patents covering all aspects of fuel cell technology including: cell stack design, catalysts, fuel processing, and inverters.

2.3.3. Useful Features/Benefits

Telecommunications companies require system availability approaching "5 nines," or 99.99999 percent of the time. For a power system, that level of reliability translates to no more than 8 seconds of down time per year. To maintain existing power systems at that level of performance a company must have service repair persons visit sites once a month to ensure batteries are charged, the diesel engine is in good repair, and the diesel fuel has not degraded.²

In a telephone system based on copper wires electric current was passed along the same wire as the phone signal. For this copper system a combination of batteries and diesel engines was expensive but acceptable because of known reliability and relatively few installations. However, with fiber optic digital systems the electrical current must be provided separate from the telephone signal and this requires the installation of thousands of nodes, each requiring a separate power system.³ One node will be able to service approximately 200 homes.

It is estimated by Southern New England Telecommunications that they will require 10,000 nodes to service Connecticut with fiber optic telephones. Bell Atlantic estimates that Pennsylvania will require 40,000 nodes.⁴ At these installation rates, over 600,000 nodes will be required to serve the US population.⁵ Each node requires 5 to 20 kW of power. For telecommunications companies, siting and maintaining these nodes is a significant challenge. It is increasingly difficult to site diesel generators in residential areas for both noise and pollution emission reasons and maintaining the nodes will cost millions of dollars annually.⁶ Adequate power systems are one of the main deterrents from faster introduction of fiber optic systems to residences and small businesses.

In addition, telecommunications companies have thousands of cellular and PCS telephone sites that require individual power systems. According to the Personal Communication Industry Association there are 40,000 cellular/PCS sites in the US today and that number will grow to 120,000 over the

² Personal Communication, SNET, 10/97.

³ Co-Evolution of Electric & Telecommunications Networks, Remarks of Steven Rivkin to EPRI's Conference on Business Solutions for a Competitive Environment, 10/97)

⁴ Personal Communication, SNET, 10/97.

⁵ Personal Communication, JJ. Cacchio Associates, 12/97.

⁶ Personal Communication, Titanium Corporation, 11/97.

next 15 years.⁷ The siting and maintenance issues for these facilities are the same as for the fiber optic nodes.

A hydrogen fueled, fuel cell backup system, may be sold based on reduced maintenance cost and ease of siting without a reduction in system availability. For the fuel cell system the only required site visit will be for refilling the hydrogen storage after use. All aspects of the system will be remotely monitored, including the hydrogen level, to eliminate all unneeded maintenance visits.

It is possible for this telecommunications system to be utilized for continuous power for remote applications with a larger hydrogen tank and possibly in conjunction with a solar power system. Such a system is currently being investigated by the Desert Research Institute. A continuous power system, for example, could power the dispersed weather systems of the University of Alaska.⁸

2.3.4. Product Development

International Fuel Cells is committed to the introduction of new fuel cell products for commercial applications. Research and development in fuel processing, cell design, and catalysts are an active component of IFC's ability to make our products cheaper, smaller, lighter, and adaptable to a variety of fuels and applications. IFC works in conjunction with the Department of Energy, the Department of Defense, and national laboratories to advance fuel cell technologies. IFC spends several million dollars per year on research and development.

IFC has defined a product development plan for the introduction of a fuel cell for telecommunications. The development plan has five basic elements based on functional activities that need to take place: design, technology development, testing, manufacturing, and marketing. IFC is confident that it can deliver a product by the year 2002 if a development program in 1998 is begun. However, part of IFC's development program also includes a role for the U.S. Department of Energy in promoting hydrogen infrastructure. IFC believes USDOE's support, is critical to the successful implementation of a fuel cell telecom product.

2.3.5. Product Selection Criteria

IFC selects products for introduction based on three criteria: market demand, technical feasibility, and internal rate of return on investment. Most crucial is the interaction of market demand and technical feasibility - can IFC provide a product that meets the needs of the customer at an acceptable price? IFC's delivery and maintenance of the fuel cells for the space shuttle orbiter program is a testament to our 30 year tradition delivering products with the highest level of technical performance and operation.

Our emphasis will continue to move from research and development to commercial products. This process began with the introduction of the PC25 fuel cell power plant in 1992 and will accelerate as IFC implements a plan to deliver new commercial products in the coming years. The potential market for fuel cell products is enormous. Essentially every device that uses either electricity or gasoline may one day be powered by a fuel cell. IFC will initially target markets, such as telecommunications, that can beneficially utilize the technology that IFC has developed to date. As our R&D develop our technology base and our commercial experience grows, IFC will add new products.

For small cell fuel cell devices, IFC evaluated several potential product offerings before selecting telecommunications as a preferred market. The applications IFC evaluated include laptop computers, portable generators, battery trimmers, wheelchairs, and video cameras. Each of these products was eliminated for at least three general reasons. First, most of these applications would require fuel cells less than 1 kW. Fuel cells that are 1 kW would be best designed with an air cooled system, while

⁷ Personal Communication, Personal Communication Industry Association, 1/98.

⁸ Personal Communication, Hutton Communications, 10/97.

IFC's focus will be on water cooled systems. Second, several of the evaluated systems required some degree of portability and eliminate the use of hydrides for a storage device because the weight hinders the use of the product. For example, 0.25 pounds of hydrides are required to operate a portable computer for 4 hours - a higher weight than batteries with no added performance, shown in Figure 2-2. Finally, the customer base for these products is diffuse and magnifies the difficulties in introducing a hydrogen based system. At the current stage of technology, fuel cells may not offer advantages to portable power applications.

Device	System Energy (watt hours)	Operation time (hours)	Hydride weight (kilograms)
Portable Computer	25	4	0.15
Video Camera	100	2	0.5
Portable generator	600	2	2.5
Wheelchair	744	3	3.4
Golf cart	7,920	4	35
Cellular Tower backup	240,000	24	500

Figure 2-2. Potential Applications for Hydrogen Fueled Fuel Cells

2.3.6. Overall Strategy

A five year development plan for a telecom fuel cell product is shown in Figure 2.3-1. This program is an aggressive attempt to produce a commercial product in as short a time as possible. The program assumes full commitment at the outset to achieve the time line presented. We start the program with an understanding of three points: (1) There is a strong demand in the telecommunications market for power systems; (2) IFC has the technology and knowledge to build a telecom product today; (3) IFC has identified a technology development plan to achieve the cost targets necessary for this market.

IFC's product development plan focuses initially on the advanced technology required for the product to meet its cost and volume goals. This program is expected to last for one year. Alpha test units can begin being built by the 4th quarter of the first year and continue into the 1st quarter of the following year.

Within the program, Beta unit development, utilizing materials from the advanced technology program, would begin in the 4th quarter of the second year and continue into the following year.

Utilizing test results from the Beta program, IFC will modify product designs and begin laying out a manufacturing plan to produce 1,000 units per year. In the plan, manufacturing is in place by the fifth year. An appropriate marketing and sales program will be instituted throughout the product development program. The final component of the product development program is the support of the Department of Energy in a hydrogen awareness program.

Fuel Cell for Telecom Product Development Plan

Figure 2.3-1. IFC's Five Year Development Plan

YEAR 5

4 Test Analysis

4.1 Define Operation Schedules

4.1.1 Cycle

4.1.2 Duration

4.2 Data collection definition

4.3 Test

4.4 Analysis

4.4.1 Data analysis (per/endurance)

4.4.2 Post test physical analysis

4.4.2.1 PEM cell components

4.4.2.2 hydride / can corrosion

4.4.2.3 Interface

4.4.2.4 Mechanical components

5 Marketing

5.1 Define market

5.2 Product definition

5.2.1 size/weight

5.2.2 Power/price/life/warranty

5.3 Distribution network

5.3.1 Sales network

5.3.2 Distribution

5.3.3 Refueling

5.4 Customer Service

5.5 Advertising

5.6 Sales support

6 DOD / H2 Awareness Program

6.1 Awareness

6.1.1 Education program

6.1.2 Safety testing

6.2 Infrastructure

6.2.1 Construction

6.2.2 Research

6.2.2.1 Hydrogen storage

6.2.2.2 Reforming

Figure 2.3-1. IFC's Five Year Development Plan (Cont'd)

The telecom unit will be designed to supply 10 kW, 24 volts dc power, operate for 24 hours and have electronic controls that allow it to pickup a load within 1 cycle of a power disturbance. The unit will have 80 cells each with an active area of 0.362 sq. ft. operating at 0.630 volts at 600 ASF for an output of 136.84 watts per cell. Voltage will be regulated to maintain a range of 22.5 to 28 volts as required by telecom equipment operators.

The metal hydrides will hold approximately 14 pounds of hydrogen and be held inside a tubular container surrounding the fuel cell. Part of the heat will be used to keep the metal hydrides warm. The fuel cell will be water cooled and there will be a need for a small radiator to dissipate the excess heat.

The design program for the alpha units is estimated to take 3 months. The design program for the Beta units that incorporates advanced technology will take approximately 6 months and require 6 engineers. The Beta units will incorporate safety and interconnection issues that will allow them to be placed at customer locations. Design for the production units will be based on experience of the Beta units. The total cost of the design effort will be approximately \$4.4 million over a three year period.

2.3.8. Technology Program

The advanced technology program will focus on three major tasks. The first task is to reduce the cost of the water transport plates required for each cell. IFC and Sandia have identified a strategy to change the composition and manufacturing processes of the plates to maintain the porosity and durability of the plates while reducing the cost.

The second task is the reduction in cost of the metal hydride storage system. IFC will work with Sandia to maximize the storage capacity of its metal hydrides and identify manufacturing partners that will be able to produce the hydrides and an appropriate container. Based on information from Sandia, the quantity of hydride required to operate for 24 hours would cost approximately \$2,000 per kW today. These costs must be reduced to approximately \$300/kW to make the telecom product viable.

The third major task is the systems integration. While IFC has years of experience integrating fuel cell systems it has not to date developed an integrated system that utilizes waste heat to maximize the flow of hydrogen from a hydride system. In addition, since the intended application, telecommunciations, requires sensitive power requirements there is an increased need to have precise control of oxygen and hydrogen reactant flows.

The two year technology program is estimated to cost approximately \$2 million. Over that period, the program will require four engineers and three technicians.

2.3.9. Manufacturing Plan

International Fuel Cells has nearly 30 years of experience designing, manufacturing, and assembling fuel cell power plants. IFC's process for delivering fuel cells involves designing a system, manufacturing key components in house, using subcontractors to manufacture other components to our specifications, and final assembly at our facility in South Windsor. This procedure allows IFC to control the design of the system and the manufacturing processes of patented components while making use of the efficiency of scale of suppliers to deliver lower cost products.

For a telecom fuel cell, IFC will adapt current methods of fuel cell production. This means that we will use a combination of internal design and manufacturing with selective use of subcontractors to reduce costs and improve quality. IFC will manufacture the fuel cell stack, including electrodes and water transport plate while purchasing some components, such as membranes from a supplier. IFC will be the final assembler of components. IFC has outlined a two year program to finalize the tech-

niques that will be utilized in cell stack production. Included with this program are facility design, layout, and construction based on current experience with existing IFC fuel cell manufacturing.

From past experience, IFC is well aware that cost is a key issue in the acceptance of a telecom product to the power marketplace. IFC estimates that the ultimate installed price of the system must be \$1,500/kW or \$15,000 for the 10 kW telecom unit. To meet this price, the cost of both the cell stack and the hydride are issues that must be substantially reduced. The cost issue is further addressed in the financial section of this report.

IFC, in conjunction with W.L. Gore, and Sandia have developed techniques to reduce the cost of both the raw material and the manufacturing processes required to make these parts. IFC is confident that it can produce cell stacks for \$500/kW when producing 10 megawatts of cell stacks per year. Included with in this estimate is costs provided by Gore for membrane material and internal estimates for manufacturing bipolar plates at IFC.

IFC will work with Sandia and manufacturers of hydrides to reduce costs to approximately \$300/kW per 24 hours of operation. In addition, increased investment by the Department of Energy in hydrogen storage technologies will help enable telecom and other product offerings.

Developing the manufacturing plan and process to deliver a \$500/kW fuel cell stack and integrate it into a telecom project will cost an estimated \$7.2 million dollars over 3 years. During this time period the number of engineers and technicians required on the project will vary from 8 to 17 depending on the particular activity. Some of this cost can be off-set by utilizing similar production methods for related products.

2.3.10. Test Analysis

IFC is testing several PEM units under 4 kW but would like to begin testing three 10-kilowatt, 24 volt, hydrogen/air PEM fuel cells with hydrides for telecommunications in 1999. The design for these units will be based on the 25 kilowatt stacks constructed for DOE's transportation program. The purpose of the initial testing will be to prove the concept of the device and not to have a unit that could be utilized in a commercial setting.

Following these tests, IFC envisions a period of advanced technology work to decrease the cost of both the cell stacks and the hydrides. Significant testing of materials and manufacturing processes will occur during this period which is anticipated to last one year. Approximately 100 beta test units would be built utilizing the advanced technology developments. Testing of these units will be done remotely from customer sites, and after one year of operation the units will be stripped and the materials analyzed. Final design will utilize the information learned in the testing period.

2.3.11. Marketing

There will be marketing activity throughout the development program for the telecom product. Marketing's first function is to further define the product definition and functions to enable the design engineers to have the most complete information available about customer requirements. Marketing will also be involved in working with the Department of Energy to promote the use of hydrogen for a variety of applications.

As the telecom product advances, marketing will identify appropriate customers for the Beta test units. These customers must be willing to pay a premium for the device, understand there may be some technical difficulties, and allow IFC to have access for data sampling. Federal government installations may be appropriate for siting units.

The marketing department will be responsible for establishing the business relationships with the partners required to make the telecom product a success. These relationships would include a dis-

tribution partner, such as Lucent Technologies, or a network of independent sales representatives that would be responsible for directly selling the device. The marketing department will also work with the design team and industrial gas suppliers to establish a refueling strategy.

Marketing activities will require one full time employee for the first two years and then growing quickly to 14 people by the time full scale production is reached in the sixth year. The marketing program is expected to cost \$3.8 million dollars through the end of the sixth year including \$500,000 in expenses to cover advertising and travel.

2.3.12. Facilities

IFC/ONSI's current manufacturing facility is 80,000 sq. ft. of fabrication and assembly space. This facility is designed to produce 40 MW of power plants per year. A diagram of the manufacturing facility is shown in Figure 2-4. This facility and the associated manufacturing equipment cost approximately \$20 million dollars to construct. For telecom applications, IFC's planning base for telecommunication applications was to produce 10 MW of fuel cells per year or 1,000 ten kilowatt units each year.

Since this is 25 percent of our PC25 production capacity, and considering our experience building fuel cell power plants, it is assumed that one quarter of the space and equipment will be required for the telecom fuel cells. Therefore, it is estimated that 20,000 sq. ft. of space plus equipment will cost \$5 million. It is unknown where these facilities will be located.

Figure 2-4. Sketch of the Cell Stack Manufacturing Lines

2.4. Market Analysis

2.4.1. Market Definition

The initial target market for IFC's 10-kilowatt hydrogen fueled fuel cell will be backup power for cellular towers and fiber optic repeating nodes.

2.4.2. Industry Analysis

The demand for cellular and fiber optic communications are the most rapidly growing sectors of the telecommunications market. Consumers and business persons are demanding to have voice, data, video, and pictures electronically delivered to them quickly, reliably, and at multiple locations. The telecommunications industry has responded by providing new services including cellular communications, high-speed transmission through fiber optic wires, and remote radio frequency stations.

The electricity required for a traditional copper wire communication system can be sent over the same wire as a telephone signal from a central switching office to an individual phone. With cellular and fiber optic systems, electricity needs to be delivered to thousands of individual sites where signals are received, sent, or amplified. Based on figures from SNET and Bell Atlantic, it is estimated that 625,000 nodes will be required fiber optic service in the United States over the next twenty years (400 people per node). In addition, according to the Personal Communication Industry Association, 80,000 cellular/PCS sites will be added to the existing 40,000 sites over the next 15 years.

Each of these nodes/sites requires a primary and secondary power source because power cannot be interrupted for more than 8 seconds per year. Currently, telecommunications companies use a combination of grid electricity and battery/diesel UPS systems to fulfill power requirements.

For telecommunications companies, siting and maintaining these nodes is a significant challenge using battery/diesel systems. It is increasingly difficult to site diesel generators in residential areas for both noise and pollution emission reasons. Maintenance requires replacing batteries and periodically removing the diesel fuel that degrades over time. The lack of adequate power systems are one of the main deterrents from faster introduction of fiber optic systems to residences and small businesses.

2.4.3. Market Segments

Initial markets for fuel cell telecommunications products will focus on two market segments. The first is the cellular phone companies. The major cellular companies in the United States are:

- AT&T Wireless Data Division
- Bell Atlantic NYNEX Mobile
- BellSouth Mobility
- Cantel
- Cellcom
- Cellular One
- GTE
- Southwestern Bell Wireless
- SNET
- GTEsprint PCS
- United States Cellular

The second market is digital fiber optic repeating stations operated by local and long distance phone companies. Major participants in the United States are:

- ATT
- Ameritech
- Bell Atlantic
- BellSouth Corporation
- Cincinnati Bell
- Frontier
- GTE
- MCI Communications
- Pacific Telesis Group
- Southwestern Bell
- SNET
- Sprint Communications
- US West Communication Group
- Williams
- Worldcom

Each of these companies has one or more individuals responsible for developing power systems to ensure the reliability of communications network. It is this person who IFC will need to convince of the superior characteristics of fuel cell power.

Currently this market is serviced by companies that supply individual components to a power system that is packaged either by an independent distributor or by the telecommunications company itself. For instance a system may consist of batteries from C&D PowerCom, a 5 kW generator from Libby, a UPS system from Toshiba, and power electronics from Lucent. There is no single company that supplies an integrated system from its manufacturing facilities.

Current retail prices of battery/diesel systems vary from \$1,000/kW to \$2,500/kW installed. The variation in price depends on the reliability of the system, the number of hours of battery backup, and the fuel requirement for the diesel generator. Additional information on the existing backup power systems is provided in the competition section.

2.4.4. Strengths

IFC's telecommunications fuel cells can provide clean, reliable, and cost effective solutions to the backup power needs of the cellular and fiber optic system operators. PEM fuel cells operating on hydrogen start quickly, have no emissions, deliver dc power, and will not degrade with inactivity. These characteristics make IFC's PEM fuel cell able to fulfill a niche that is not being adequately serviced with existing technology.

IFC, through its ONSI subsidiary, has experience in commercializing new products. ONSI contains both the marketing and the customer service arms of IFC. ONSI has a marketing staff of six persons. This staff has experience both inside and outside the fuel cell industry. ONSI has also established a growing network of independent representatives. ONSI has direct contact with several large telecommunications companies and they have specifically requested the products being discussed in this business plan. ONSI's customer support consists of 12 individuals who answer customer questions and make field visits when necessary. ONSI's customer support is available 24 hours a day.

In addition, IFC and ONSI have teamed together with Toshiba and Ansaldo Corporation to commercialize fuel cell power plants. Through these companies and several independent channels, IFC has the capability of understanding and selling products in foreign markets. Both Toshiba and Ansaldo currently sell electronic equipment directly to telecommunications companies.

IFC is part of United Technologies, \$25 billion dollar international company. This relationship gives IFC access to leading edge research, business contacts, and financial support.

2.4.5. Weaknesses

There are two major weaknesses of fuel cell technology in telecommunications applications. The first weakness is the use of hydrogen as fuel. Hydrogen has several disadvantages as a fuel source. First, there are not readily available options to recharge depleted hydrogen storage tanks. Centralized recharging will need to be provided by customers. In addition, hydrogen continues to be perceived by the general public as a dangerous fuel source. The installation of the fuel cell products in residential zones may make some local zoning boards hesitant to approve projects, making the use of fuel cells more difficult than standard batteries. IFC's use of metal hydrides for hydrogen storage should help to dispel any fear of hydrogen. The Department of Energy could be especially useful in providing educational programs designed to counteract any belief that hydrogen is dangerous and inappropriate for telecommunications applications.

The second weakness is the issue of the PEM fuel cell's tolerance to freezing. IFC is working on several technological solutions to the freezing issue but have not implemented a final choice. Therefore, IFC's product will initially need to be buried below the frost line to prevent damage to the equipment.

2.4.6. Opportunities

The potential market for IFC's telecommunications products in foreign countries has not been included in this analysis. International companies are facing the same issues as US companies, especially as it pertains to cellular towers. The current market for IFC's fuel cell power plants is 50 percent outside the United States. If this experience is used as a benchmark, there is significant upside potential for telecommunications products.

More importantly, these telecommunications products will give IFC the technological, manufacturing, and marketing experience to enter multiple additional markets with similar small products. A prominent example is the use of fuel cells for residential applications. A 5-kilowatt residential fuel cell operating on natural gas will be very similar to a telecommunications fuel cell operating on natural gas or methanol. The market for a reliable, inexpensive fuel cells for residential applications may reach billions of dollars.

2.4.7. Customer Profile

Power is a service that telecommunications companies take for granted. It is only when there is a problem with the system that people responsible for power delivery have a high profile. Executives do not like that type of notoriety. Therefore, the prototypical customer for a telecommunications fuel cell will be extremely risk averse. This executive wants a technology that will always work and one that can be installed and maintained without much difficulty. Price is an issue but only after other goals have been met.

2.4.8. Competition

The primary competition in the market is are the traditional power solutions including battery companies, UPS companies, and engine generator manufacturers since those are the primary products the fuel cell will replace. Battery companies involved in the telecommunications market include

C&D Power, Yuasa-Exide, Johnson Controls, and Power Battery Company. Companies that make stand-by generators of 10 kW and less for the telecommunications market include: Libby, Generac, Katolight, and Onan. UPS suppliers include: Toshiba, American Power Conversion, and Exide.

Other significant players in the market are companies that package together systems consisting of products from different vendors to meet the needs of the final user. Package integrator companies include: Hutton Communications, Lockheed Martin, Lucent Technologies, and Elysium Incorporated. These companies represent potential distribution channels for IFC's products.

2.4.9. Existing Backup Power Systems

Existing backup power systems are formidable competitors. While these systems do not meet the ultimate needs of telecommunications companies, their limitations are well understood and can be factored into telecommunications companies' risk management. Fuel cells can penetrate this market by offering better performance, lower operating costs, and equal or lower capital costs. The estimated cost for a 10 kW battery/diesel backup system with 8 hours of battery operation is estimated to be \$20,000 plus installation or \$2,000/kW:

Generator	\$8,000 (10 kw Generac LP gas or equivalent)
Battery systems	<u>\$12,000</u> (4 C&D Power 24 volt @1100 AMP hour)
System cost	\$20,000

2.4.10. Fuel Cell Competition

In addition to IFC, other companies are engaged in the research and development of fuel cell systems. None of these companies have the depth of knowledge that IFC has gained with thirty years of operation, none of these companies have ever sold a fuel cell power plant for commercial applications, and none of these companies has expressed interest in telecommunications applications.

Nevertheless, several companies have made significant advancements in product development and may be able to launch commercial products in the near future. Review of major fuel cell competitors follows:

- **Ballard Power Systems** of Canada has the technical knowledge and the financial resources to launch a competing product in the telecommunications arena. However, it has publicly expressed little interest in pursuing markets other than stationary power plants (250kW) and transportation applications.
- **HPower Corporation** is developing fuel cells for portable power applications such as transportation signs, wheelchairs, and computers. All of these applications require systems with power significantly less than 10kW.
- **Plug Power** is primarily involved in the designing fuel cells for residential applications.
- **Energy Partners** is developing fuel cells for specialty vehicle applications.

Other fuel cell companies, such as **Energy Research Corporation**, **MC-Power**, and **Westinghouse** are involved with product development in size ranges over 200 kilowatts.

2.4.11. Observations and Conclusions

It appears that there is substantial market opportunities for fuel cells providing backup power for telecommunications facilities. The lack of adequate power is a major deterrent to the expanded use of advanced communications facilities. Existing power systems will not be able to fill this void and there are no other systems on the immediate horizon which appear to compete for this market.

The two major barriers that need to be overcome to achieve a profitable product line that provides a critical resource to the nations economy are hydrogen storage technology and hydrogen refilling.

The advanced hydrides being developed by Sandia are improvements over the past but are still more bulky and expensive than is desirable. Similarly, methods for delivering hydrogen to distributed sites needs to be addressed. One possible method would be to generate on-site using electrolyzers, however, this option is not near commercialization. DOE can help to eliminate these barriers through research grants and public education.

2.4.12. Risk

As with all business ventures, there is risk associated with pursuing a fuel cell product for telecommunications applications. For this case, however, the risk is reduced because the resources and technology required to pursue this product will be leveraged with programs pursuing similar products in other markets. Therefore, the risk that fuel cells will not work in the telecommunications market will not change the overall strategy of International Fuel Cells. If, however, there is a technological problem with the basic PEM fuel cell or its cost cannot be reduced, the potential business losses could be substantial. IFC does not believe this is an issue and equates the risk of pursuing a telecommunications backup product to the ability to solve the hydrogen storage and hydrogen refueling issues.

2.5. Marketing Plan

A detailed Sales and Marketing Plan will be developed as implementation of the Business Plan proceeds.

2.6. Financial Plan

2.6.1. Assumptions

The financial analysis includes projected sales and costs associated with a fuel cell product for telecommunications applications. A 10 year financial proforma has been developed (Figure 2.6-1). Initial sales will be a 10 kW hydrogen fueled PEM unit for backup power starting with demo sales in the first year and full production sales in the fifth year. Sales of the follow-on products in this market, including different power sizes and a model that operates on petroleum based fuels have not been included in the Financial Plan.

Sales projections are based on market penetration of backup power systems for cellular towers and fiber optic repeating nodes in the United States. Southern New England Telecommunications estimates it will require 10,000 backup power systems in Connecticut to support fiber optics in every home. That is approximately 1 node for every 400 people in Connecticut. Bell Atlantic estimates it will need 40,000 backup power systems in Pennsylvania. That is approximately 1 node for every 300 people. Utilizing the more conservative 1 to 400 ratio in Connecticut, it is estimated that 625,000 nodes are required to serve the 250 million people in the United States with fiber optic cable. An additional 80,000 cellular/PCS sites will require backup power in the future as well.

It is estimated that fiber optics will be slowly introduced in the U.S. over a twenty-year period. Therefore, an estimated 5 percent of population will gain access to fiber optics and cellular communications each year. This additional service will require 30,000 new nodes or backup power systems. It is projected that each of IFC's 10 kW in this market will capture up to 10 percent of the total unit sales.

Sales prices of the units, including the fuel cell, power electronics, and hydrogen storage are projected to be \$1,500 per kilowatt or \$15,000 per unit. This sales price is targeted below the existing price for substitute products. IFC believes that the advantages of the fuel cell will enable it to capture up to 10 percent of the market. It is possible that these prices will decrease in the future with increase manufacturing volume of fuel cells for all applications. However, IFC is not assuming synergies from other businesses or products in this business and financial analysis.

In this plan, IFC is intending to have 3 working prototypes of a 10kW hydrogen unit by the end of the first year. Beta testing of the product is to start by the beginning of the second year and be completed by the end of that year. Commercial introduction of the product will begin in the fourth year.

Financial Proforma (years 1-10)

Sales	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
10 kw Hydrogen PEM Cells	0	100	0	500	1000	2000	2000	2000	2000	2000
- Unit Price (\$)	\$0	\$20,000	\$0	\$15,000	\$15,000	\$15,000	\$15,000	\$15,000	\$15,000	\$15,000
Total Sales	\$0	\$2,000,000	\$0	\$7,500,000	\$1,500,000	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000
Total Cost of Goods Sold	\$0	\$2,000,000	\$0	\$5,000,000	\$10,000,000	\$20,000,000	\$20,000,000	\$20,000,000	\$20,000,000	\$20,000,000
Gross Profit	\$0	\$0	\$0	\$2,500,000	\$5,000,000	\$10,000,000	\$10,000,000	\$10,000,000	\$10,000,000	\$10,000,000
Operating Expenses										
Sales & Marketing	\$110,000	\$120,000	\$120,000	\$750,000	\$1,500,000	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000
- Design	\$500,000	\$500,000	\$500,000							
- Advanced Technology	\$980,000	\$932,000								
- Testing	\$378,000	\$295,000	\$406,000							
- Manufacturing	\$0	\$840,000	\$2,100,000	\$1,260,000						
G & A (Without Depreciation)	\$20,000	\$200,000	\$200,000	\$750,000	\$1,500,000	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000	\$3,000,000
Depreciation	\$0	\$0	\$0	\$714,286	\$714,286	\$714,286	\$714,286	\$714,286	\$714,286	\$714,286
Total Operating Expenses	\$1,988,000	\$2,887,000	\$3,326,000	\$3,474,286	\$3,714,286	\$6,714,286	\$6,714,286	\$6,714,286	\$6,714,286	\$6,714,286
Income from Operations	(\$1,988,000)	(\$2,887,000)	(\$3,326,000)	(\$974,286)	\$1,285,714	\$3,285,714	\$3,285,714	\$3,285,714	\$3,285,714	\$3,285,714
Capital Expenses	\$0	\$0	\$0	\$5,000,000	\$0	\$0	\$0	\$0	\$0	\$0
Total Income	(\$1,988,000)	(\$2,887,000)	(\$3,326,000)	(\$6,974,286)	\$1,285,714	\$3,285,714	\$3,285,714	\$3,285,714	\$3,285,714	\$3,285,714
Interest Income	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
Interest Expense	\$0	\$0	\$0	\$500,000	\$500,000	\$500,000	\$500,000	\$500,000	\$500,000	\$500,000
Income before Taxes	(\$1,988,000)	(\$2,887,000)	(\$3,326,000)	(\$6,474,286)	\$785,714	\$2,785,714	\$2,785,714	\$2,785,714	\$2,785,714	\$2,785,714
Taxes on Income*	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
SubTotal	(\$1,988,000)	(\$2,887,000)	(\$3,326,000)	(\$6,474,286)	\$785,714	\$2,785,714	\$2,785,714	\$2,785,714	\$2,785,714	\$2,785,714
Terminal Value (After Taxes)										\$9,800,000
Net Income After Taxes	(\$1,988,000)	(\$2,887,000)	(\$3,326,000)	(\$6,474,286)	\$785,714	\$2,785,714	\$2,785,714	\$2,785,714	\$2,785,714	\$12,585,714

IRR = 9%

Figure 2.6-1. Financial Proforma (Years 1-10)

2.6.2. Financial Proforma

Implementation of this business plan is expected to generate revenues from sales of fuel cell products to the telecommunications market is expected to reach \$15 million in the fifth year, \$34 million in the seventh year, and \$100 million in the tenth year. IFC will maintain a 50 percent gross margin required to meet corporate requirements and to pay the distribution channel. To meet this requirement, the cost of goods sold will need to be \$1,000 per kilowatt in, year the third year. Estimated costs are:

	<u>Year 1</u>	<u>Year 4</u>
Cell stack	\$3,000	\$500
Power electronics	400	200
Metal hydride	<u>2,000</u>	<u>300</u>
Total cost of goods sold	\$5,400	\$1,000

These costs are estimated based on IFC's knowledge of fuel cell systems, estimates from Sandia National Laboratory, W.L. Gore & Associates, and our fuel cell manufacturing experience.

Non-manufacturing operating expenses are estimated as follows based on IFC experience in manufacturing, marketing, and servicing fuel cell power plants:

Sales & Marketing	10% of sales
Research & Development	5% of sales
G & A	10% of sales
Depreciation	Seven year straight line depreciation of capital
Interest	10% of capital investment

2.6.3. Capital Requirements

The total investment or net operating losses through the first five years are expected to be approximately \$15 million. Two-thirds of this money will be spent on product development activities including the establishment of distribution channels and the other third on building a manufacturing facility. It is assumed that outside sources of capital will be required.

2.6.4. Financial Results

It is expected that a business focused on the telecom market would lose money for the first 4 years of operation. These losses would total nearly \$15 million before the company began to earn a profit in the fifth year of operation. The net income after taxes is expected to be \$2.7 million in the sixth year and each of the following years when sales are expected to reach 2,000 units. The IRR for the net income after taxes for ten years is calculated to be 9 percent which is below investment threshold. Thus, using the assumptions in this business plan, investment in a telecom product is not financially justified without means to offset capital requirements.

2.6.5. Conclusion

Through our market investigations, we have concluded that there is a market for a fuel cell product for backup power in telecommunications.

This market is highly concentrated and requires advanced power systems to enable enhanced reliability of our nation's communication infrastructure. Fuel cells offer many of the benefits required in this application. The conservative financial projections indicate that beginning a business today with a focus on fuel cells for telecommunications will produce a self-sustaining business that achieves an internal rate of return (IRR) of 9 percent, below the investment threshold. Therefore,

this business activity must be supported by one or more outside sources to make it a viable business. One of these sources may be the Department of Energy to support the substantial development activity that is required to reduce the cost of critical parts of the power plant, in particular, hydrogen storage. A second source of activity would be to leverage activities with related products, such as fuel cells for transportation, to utilize technology advances in one area for application in another. IFC intends to have some of these synergies available in the future.

For the next phase, IFC proposes continuing the advanced technology work begun in Phase I of this program. This activity would focus on the three core areas:

1. Water Transport Plate - Under this activity, IFC will perform laboratory experiments, and work with Sandia National Laboratory on material composition and manufacturing processes to reduce the cost of water transport plates while maintaining porosity and curability.
2. Hydrogen Storage - IFC will work with Sandia National Laboratory and other international laboratories in determining the commercialization [potential of new methods of storing hydrogen,. Initially IFC will evaluate methods of storing in excess of 5 percent of hydrogen by weight.
3. PEM Membrane and Catalyst Development - IFC will continue to work with W.L. Gore & Associates to develop catalyst and membrane materials that will meet the cost and performance requirements of commercialization.

Concurrent with these activities, IFC recommends that DOE fund programs that advance a hydrogen infrastructure and facilitates the understanding and benefits of hydrogen systems to the general public.

3.0 TECHNOLOGY REPORT

3.1. Summary of Technology Developments

The results of this initial program enable us to assess our status for meeting the technology goals required to move forward to commercialization of a 10 kW power plant. The WTP program conducted by SNL and IFC made very good progress towards making a plate with the material specifications set by IFC. Several samples were fabricated by SNL and characterized by IFC. The structure characteristics, porosity and mean pore size, were very nearly attained. The electrical resistivity while still a factor of 10 higher than desired is promising and a path to meet the goal is defined. The conductivity can be increased by additive fillers such as graphite or alterations to the hot pressing steps. Although the material strength properties were not measured because of the size of the samples, the samples appear to be more fragile than desirable. Again a clear path to increasing the strength is available with changes in composition and heat treatment.

The one question about the SNL processing at this time is whether the current processing procedures are suitable for large rectangular parts. Shrinkage during the heat treatments steps is a concern. Since this possibility exists, SNL has identified a alternative process whereby one can join two smaller square parts to meet the desired part size. The connection could be accomplished over a small area and would not significantly affect the necessary water transport properties of the plate. Overall the results of the program are viewed as positive. Both SNL and IFC believe, that with further research into processing and materials, separator plates can be fabricated that will meet the design requirements.

The PEM cell performance has been addressed by both W. L. Gore & Associates and IFC. Performance data were obtained with the Gore state of the art M&EA in cell tests at IFC. The performance levels were very good and a power plant design can be based on that performance. IFC electrodes with the Gore membrane did not achieve as high a performance level. The reason for this result is believed to be associated with electrode optimization. With continued research at IFC we believe that we could achieve comparable performance to the Gore materials.

IFC sent a small quantity of their supported platinum alloy catalyst to Gore so they could fabricate an M&EA with it. Gore prepared a number of M&EAs and ran cell tests. Gore found that the performance was promising but further electrode optimization would be required to surpass their present performance with their own catalysts. A cell test at IFC with the Gore M&EA with IFC catalyst also performed poorer than the fully made Gore M&EA. Both Gore and IFC believe that further PEM cell performance improvements are possible either with or without the IFC alloy catalyst. This research would be addressed in future programs. Based on IFC estimates for power plant production Gore has estimated that the cost of the M&EA can be reduced by about 23 to 38% in going from the α to the β units and from 54 to 68% in going from the α to the commercial units.

The initial hydride study at SNL has identified possible materials and a plan to meet the fuel cell hydrogen requirements. The study has shown that the volume, weight and cost of the hydride, for any hydride of the hydrides considered, are all presently very high. Research and development should be able to improve the size and weight parameters. SNL projects that the high present costs can be reduced partly by large volume purchases. This is an area that needs further investigation since IFC does not have an experience base in hydride storage systems and SNL's experience is primarily in research and development rather than commercial hydride storage units.

In future development work alternate fuel storage/delivery systems should be considered beyond the hydride system. One of the new advanced materials proposed for hydrogen storage are carbon

nanotubes. These tiny tube-like carbon configurations have high surface areas in comparison to their volumes which allows a high hydrogen storage content with light weight. This alternative is being actively researched at the present time. Another possible fuel supply would utilize some other hydrogen source such as natural gas or diesel fuel and use a compact high efficiency reformer to supply the hydrogen. This possibility would be particularly attractive for locations where these fuels would be readily available. The logistic and safety requirements for fuel replenishment would be eliminated.

We have reviewed the results of this program and have identified a technology program to meet the goals necessary to meet the requirements of the PEM fuel cell performance, separator plate physical properties, and hydride storage system.

3.2. Description of Technology Tasks

In the Phase I study there were three main technology tasks identified to be accomplished. They were:

1. Evaluate the hydride technology for the projected market sector. This would be a study effort only and would be carried out by Sandia National Laboratories (SNL) with input from International Fuel Cells (IFC) on the size of the power plant application. Cost, size (volume & weight), refueling alternatives and safety considerations would be addressed.
2. Evaluate the state of the art W. L. Gore & Associates (Gore) membrane and electrode assembly technology. Blending the Gore membrane technology with the IFC catalyst technology would be undertaken to establish the realistic cost of the membrane and electrode assembly as well as establish what the cell performance impact would be with the adoption of the IFC catalyst. The results of this activity would provide the cost support for the market study.
3. Evaluate separator plate samples fabricated by Sandia National Laboratories. The samples would be assessed by a series of mutually agreed upon laboratory scale component tests. These tests would be designed to determine how well the laboratory scale components, made from the SNL manufacturing process, meet the functional requirements specified by IFC. It was anticipated that several iterations would be required to obtain an accurate assessment of both the cost and also the ability to make functional parts with the SNL process.

3.3. Description of Integrated Hydride Fuel Cell System

The envisioned product is a PEM fuel cell used as an electric power generator, powered by hydrogen stored in a hydride. The hydride would be charged at the site. This implies that the integration opportunities will occur primarily during discharge when the fuel cell is operating.

Phase I of the program focused on the identification of market opportunities. A market for a 10 kW PEM-Hydride system as backup power for the telecommunications industry was identified. This size power plant would integrate the hydride to the PEM fuel cell during discharge or power generation. The integration opportunity is to use the fuel cell waste heat to facilitate hydrogen discharge. Water cooling of the fuel cell stack could integrate the coolant directly with the hydride unit as an optimal configuration. Because of the backup times required, a range of 8 to 72 hours is envisioned, charging of the hydride would take place at the site of operation.

There are three subsystems comprising the proposed hydride-fuel cell system. They are: 1. the fuel storage/delivery system(the hydride), 2. the fuel cell power plant with associated thermal manage-

ment system and 3. the control subsystem. Since the application is for dc power, no inverter system is required but the dc output must be well regulated. With only three subsystems they can be individually developed and test verified with a high degree of confidence, such that, when integrated to form the product, no first order problems will arise.

3.4. Key Integrated Hydride - Fuel Cell Technology Descriptions

3.4.1. IFC's Separator Plate Concept

A key element of IFC's PEM fuel cell concept is a separator plate comprised of two planer porous plates separated by a water reservoir compartment. Product water and any water droplets that get into the flow fields are removed through the porous plate which is adjacent to both the cathode and anode sides of the MEA. The water is removed by providing a pressure differential between the reactant gases and the reservoir. This forces the water through the porous plates directly into the water reservoir compartments separating individual cells. These compartments are all interconnected to an external reservoir which either dumps the excess or provides make-up water for evaporative losses. The separator compartments are designed to cover the entire electrochemically active area of the cell and in addition extend out into the gas inlet channels to assure that the gases are saturated before they enter the active area; consequently, preventing membrane dryout. For water cooled designs this system can serve as the water cooling system which removes the stack waste heat.

Although this concept has been tested satisfactorily, the separator plates tested to date were manufactured using a manufacturing method that resulted in a plate that was made up of fully graphitized material. This material was used for the plates in IFC's commercial phosphoric acid fuel cell products which require the use of far more stable materials than are required for PEM fuel cell technology. The cost of the plate using this manufacturing method is unacceptable for products being considered for the hydride fuel cell system. SNL's expertise in the technology of low cost manufacturing processes to produce porous carbon components is a key factor to developing the integrated PEM fuel cell into a commercial vehicle.

3.4.2. W. L. Gore & Associates PEM Membrane and MEA

The introduction of the new Gore membrane represents a breakthrough for the PEM technology. This patented technology enables several key features which are consistent with the overall direction of necessary performance developments in the fuel cell arena. The Gore membrane is a composite material of expanded very thin Teflon sheets which are "impregnated" with Nafion. Present (1, 2) and planned (3, 4) features that are being promoted by Gore include the following:

1. Ultra-thin structures, $\sim 15\mu\text{m}$, utilizing less ionomer (and thus significant cost reduction and simplification in water management for the fuel cell);
2. Ultra-stable structures with almost no dimensional change upon hydration (enabling simple or easy use and installation of the membranes);
3. Highly custom manufacturing processes (which enable variation in both chemical and physical properties to suit specific applications for both membrane and electrode);
4. Highly automatic manufacturing process (enabling low volume production at low costs).

In addition to the membrane breakthrough, Gore has developed electrode technologies such that high performing M&EAs for PEM fuel cells are now available.

3.4.3. Sandia National Laboratories Hydride Experience

The hydride system cost / capability definition was a design study primarily undertaken by SNL. SNL used their existing magnesium based and other hydride bed data together with their established analytical models to provide IFC with an estimate of the optimum hydride system configuration for a 10kW power plant. IFC and SNL collaborated to define the interface requirements for both the fuel cell during discharge and for on site refueling. Using design concepts SNL costing methodology, cost estimates for the hydride subsystem were developed.

3.5. Technology Development

The technology development during this Phase I Feasibility Study was aimed at three particular areas, improving separator plates (water transport plates) and PEM fuel cell performance as well as investigating the fuel storage system, advanced hydrides. The technology studies were a cooperative effort of Sandia National Laboratories (SNL), W. L. Gore & Associates (Gore) and International Fuel Cells (IFC). Each topic is addressed in this section of the report and future development tasks are suggested.

3.5.1. Separator Plate (Water Transport Plate "WTP")

SNL fabricated a series of water transport plate samples based on IFC's physical characteristic goals. SNL's main previous experience with porous bodies was at bulk densities well below the IFC specification. Their limited experience in the IFC density range indicated that these materials generally suffer from loss in connected porosity. These new samples were intended to optimize porosity while incrementing physical density. To a large extent, both the electrical and thermal conductivity characteristics will track with increasing density.

A brief description of the samples and the limited characterization done at SNL are shown in Table 3-1. SNL believes that the last three samples listed in that table had the best chance to meet the IFC requirements (samples CC-101C through CC-101F). In particular sample CC-101F was prepared from a commercial grade of polymer precursor and therefore represents a minimal materials cost (~\$1.00/lb.) route. The part was fabricated by a powder pressing process which could be scaled to sizes approaching 12" X 24". The process is amenable to the inclusion of performance modifying additives like graphite fiber or flake. For the test 2.5" X 2.5" specimen size scale, SNL believes that near net shaped parts can be pressed, whether this is true for the projected 6" X 12.5" production size remains to be proven. These initial studies suggest that from "green" polymer pressing to the final carbon plate there is a linear shrinkage of ~30% which must be taken into account for scaling.

Table 3-1. Water Transport Plate Samples Prepared by Sandia National Laboratories

Sample No.	Type	Microstructure	% Graphite
FC-A	Monolithic Foam	I	0
FC-B	Monolithic Foam	I	0
SK	Monolithic Foam	I	0
CC-44	Monolithic Foam	I	0
CC-100M	Sintered Powder	III	22
CC-100R	Sintered Powder	III	22
CC-100V	Sintered Powder	III	22
CC-101B3	Sintered Powder	III	22
CC-101B5	Sintered Powder	III	22
CC-101C3	Sintered Powder	II	24
CC-101C4	Sintered Powder	II	24
CC-101E3	Sintered Powder	II	0
CC-101F1	Sintered Powder	II	0
CC-101F2	Sintered Powder	II	0

Notes: Samples are grouped above based on the raw materials and also the processes by which they were fabricated. For example, the first four samples can be viewed as replicates while the last three samples are each unique in their processing. The microstructure designations I, II, III are defined by the following:

I. Open Spherical Cell Structure with Windows,

II. Open Cell Network with Irregular Struts,

III. Duplex Structure of Open Cell and Solid Flake-like Particles.

The goal for the density parameter is the range 1.29 - 1.48 gm/cc. The values listed are as measured by Sandia while those in parenthesis are as measured by IFC.

The SEM's of the structure look quite open and are expected to be within the desired range. Modification of the pressing schedule and the particulate size distribution can be used to tailor properties. SNL does have the ability to produce test panels of the small sample size, but large pilot productions would have to be done at some other site. Loads for pressing the desired part could exceed 1.5 million pounds.

The samples fabricated by SNL were submitted for physical characterization at IFC. The number and size of the samples did not allow us to measure every property for each of the different samples. We did analyze representative samples however and chose to measure the electrical resistivity first since this property has serious consequences on cell behavior if the specification is not met. The other characteristics investigated dealt with the structure of the samples and included both porosity and pore size distribution. The results of the IFC characterizations are summarized in Table 3-2.

Table 3-2. Water Transport Plate Characteristics as Measured at International Fuel Cells

Sample No.	Type	Resistivity
Specification		(mV/mil) 0.01(max)
FC-A	Monolithic Foam	ND
FC-B	Monolithic Foam	ND
SK	Monolithic Foam	0.309
CC-44	Monolithic Foam	ND
CC-100M	Sintered Powder	0.202
CC-100R	Sintered Powder	ND
CC-100V	Sintered Powder	ND
CC-101B3	Sintered Powder	ND
CC-101B5	Sintered Powder	ND
CC-101C3	Sintered Powder	0.184
CC-101C4	Sintered Powder	ND
CC-101E3	Sintered Powder	0.168
CC-101F1	Sintered Powder	0.146
CC-101F2	Sintered Powder	0.099
Notes: ND - not determined		

The last three samples, listed in Table 3-2, are believed to be the best examples of the study and their properties are closest to the specification values. The samples were too small to measure mechanical properties but it is clear that some optimization of processing variables is still required and they could be investigated in the second round of research. The electrical resistivity values are all higher than desired, above the 0.01mV/mil specification. Additional filler or pressing condition changes are believed to be an answer to meeting the resistivity requirement.

Based on the results of this preliminary work (Phase I), SNL believes that they have a good understanding for what is required to satisfy the design specifications. The basic raw material for the plate would be a powder precursor. This material is manufactured in very large quantities for the garment and floor coverings industries. The present cost varies from \$1- \$5 per pound depending on the grade and quantity.

The data from these initial parts shows that one can approach or "nominally" meet the desired specifications by pressing the polymer into preforms. A process of oxidative stabilization, 240°C for 48 hours, and pyrolysis, 1100° to 2200°C for 8 hours, yields a porous carbon plate. Total pore volume and bulk density can be adjusted by changing the pressing schedule during fabrication. In addition, control of the polymer powder particle size distribution gives one an independent variable with which to address pore size distribution and separate the effects of processing pressure on total pore volume. In the past, fibers and plate-like fillers were used to achieve the properties of pressed compacts. Some of these fillers were carbon precursors, either carbonaceous or graphitic in nature. SNL

has confidence that refinements in both electrical and thermal conductivity can be accomplished by controlling these parameters.

Mechanical properties are probably the most difficult performance variable to independently adjust. The morphology of the powder compact, i.e. sintered beads, dominates the mechanical response. One can expect to get an improvement in the range of 5-15% with the incorporation of reinforcing fillers but the nature of this porous media is that the strength is dominated by the defect nature of the compact. The greatest potential for improvements in the mechanical regime lies in increased pyrolysis temperature. High temperatures increase the degree of order within the material "ligaments" connecting the powder particles. SNL has attempted to reenforce these regions with liquid phase char formers. Although this appears to be a promising direction to follow, substantial work would be required on this front. There are substantial volumetric changes which occur during carbonization. One must control or manage strains to eliminate cracking. It may be easier to fabricate the 6" X 12" production size part with low scrap rates by examining the possibility of joining two smaller 6" X 6" plates. It has not been concluded from these studies that a single part is not possible but a contingency alternative is feasible, joining two parts, that would satisfy the requirements.

The results of the characterizations on the samples fabricated from monolithic foams suggest that these type of parts do not meet the IFC specifications. The sintered powder approach appears to lead to parts much closer to the goals and will be followed in any future development.

In a second phase of this work, SNL proposes the following:

- Task 1. Parallel efforts on the incorporation of fillers and blending of particle size distributions to address electrical conductivity and pore size distribution.
- Task 2. Explore the pressing pressure and pyrolysis temperature dynamic, within the parameter space defined under Task 1, to address total pore volume and bulk density.
- Task 3. Scale the technology to produce 6" X 6" X 0.125" final carbon plates (this involves polymer powder preforms 9" X 9" and with the current pressing pressure of 7200 psi require > 500,000 pound of force, possible at SNL).
- Task 4. Investigate joining procedures for combining 6" X 6" parts to meet the 6" X 12" part requirement.
- Task 5. Identify a suitable vendor for plate manufacture and development. Move the technology to the vendor.

3.5.2. PEM Fuel Cell Performance

In order to evaluate the performance of membrane and electrode assemblies (M&EAs) for PEM fuel cells, materials from W. L. Gore & Associates were obtained and operated in subscale cells at IFC. Initially Gore supplied two different types of materials: individual membranes, 15 μ m thick, and complete M&EAs with 15 μ m membranes. The M&EAs utilized Gore electrodes with noble metal loadings of 0.3 mgPt/cm² for the cathode and 0.1 mgPt/cm² for the anode. IFC also supplied a small quantity of IFC's cathode alloy catalyst to Gore and they fabricated M&EAs with their proprietary processes using the IFC catalyst.

The initial cell test at IFC used the fully made M&EA from W. L. Gore & Associates. The hydrogen-oxygen and hydrogen-air performance were measured at 50°C and 82°C. The data are shown in the following figures (Figure 3-1 & 3-2). All of the IFC cell tests were conducted at atmospheric pressure.

There is some effect on performance with temperature but not a significant one and the cell achieves 0.6V at about 900 ASF. These data are at low reactant utilizations and did not utilize a cell configuration with a water transport plate. Based on previous performance of subscale cells and the performance of full size parts in the actual stack configuration one can project a performance level of at least 0.63V at 600 ASF. This implies a power density based on our projected active cell area of about 1 kW/ 8 cells. For a 10 kW power plant one can estimate that a PEM fuel cell stack of about 80 cells is required to accommodate any parasite power losses. The performance data was shared with Gore and they assured IFC that the data was representative of the levels measured in their own cell tests.

An M&EA was prepared by IFC utilizing IFC catalysts: a supported platinum alloy for the cathode with 0.3 mgPt/cm² and a supported platinum catalyst for the anode with 0.1 mgPt/cm². The cell was operated at 50°C and 82°C under the same conditions that were applied to the earlier Gore M&EA cell (Figures 3-3 & 3-4).

It is not possible to directly compare the performance of the two cells on an absolute basis. The cells have different membranes, 15µm for the Gore M&EA and 20µm for the IFC M&EA. Although the membrane resistivity difference is small and can be quantified, the influence of water back diffusion, cathode to anode, on cell performance, is not as easily quantified. It is clear however the Gore M&EA performs better than the IFC M&EA with air as a reactant. The Gore cathode catalyst layer has much better limiting current behavior. IFC believes that this improved performance is a result of the Gore proprietary manufacturing processes.

Figure 3-1. W. L. Gore & Associates M&EA IFC PEMFC Test at 50°C

Figure 3-2. W. L. Gore & Associates M&EA, IFC PEMFC Test at 82°C

Figure 3-3. M&EA PEMFC Test at 50°C

Figure 3-4. IFC M&EA PEMFC Test at 82°C

Gore did have an opportunity to do some investigation of M&EA fabrication and performance evaluation with the IFC alloy catalyst. A limited number of M&EA fabrication variations were investigated. Some of these were built into cells at Gore and performance data were acquired over a limited range of operating conditions. Gore concluded that the catalyst performance results observed were sufficient to merit further investigation. During cell tests Gore concluded that the IFC alloy catalyst material behaved differently than their standard catalyst formulation. They found that the cell resistance was impacted adversely by the use of the IFC catalyst. Even with this performance negative, the overall cell performance was very good. The conditioning and equilibration times for cells with the IFC catalyst were also different from M&EAs with Gore catalyst. The Gore experience suggests that although these behaviors are different there is no reason to doubt that an optimized structure electrode, with the IFC alloy catalyst, could result in enhanced fuel cell performance.

Gore did submit performance test data, taken at atmospheric pressure, to IFC from Gore tests with M&EAs utilizing the IFC alloy catalyst. The performance was measured at a different temperature, 60°C, than we investigated but the performance is comparable to what IFC measured with the Gore M&EAs. A performance comparison is shown in Figure 3-5. The Gore cell performance as measured at Gore is compared with the data from the IFC test of a Gore M&EA tested at IFC. The IFC cell performance data shown are as plotted in earlier figures. Although the cell operating conditions are not identical, they are close enough, ambient pressure and medium reactant flow rates to allow us to plot the curves together. There is also a small platinum catalyst loading difference with the Gore cell test. In their laboratory test they used an anode with a 0.3 mgPt/cm² loading. It is expected that for operating current densities below 800 mA/cm² under pure hydrogen that there would be a significant impact on cell performance associated with the increased anode noble metal content. Considering that this catalyst layer was not optimal, we believe that by coupling the alloy catalyst with thin Gore membranes one can improve the cell power output.

Figure 3-5. Performance Comparison IFC Alloy Catalyst vs. Gore Standard Catalyst

An M&EA fabricated with the IFC catalyst by Gore was also sent to IFC for testing. This M&EA is also not to be considered an optimal assembly but is representative of an early attempt to improve PEM fuel cell performance with the IFC alloy catalyst for the cathode. The hydrogen-oxygen and hydrogen-air performance results are shown in Figure 3-6 below.

These data are plotted on an iR free basis; the cell resistance is removed. This compensates for the difference in membrane resistance between the two tests. There is still a performance difference between the two M&EAs and the presence of the IFC alloy catalyst is not seen to be an advantage. The low current density performance with the IFC catalyst is lower than with the Gore catalyst. The performance of the alloy would have been expected to be better at the low current density end where catalyst activity, not electrode structure, is expected to dominate. This suggests that not all of the alloy is active or fully wet in the electrode structure. The performance at 50°C was also lower than the fully made Gore M&EA. The data in Figure 3-5 suggest that Gore was able to observe a higher performance with a similar M&EA. That may be a result of variations in sample to sample assemblies. Again this is not an optimized system and one would expect a performance improvement with the alloy with further research.

Figure 3-6. IFC Test with Gore M&EA with IFC Alloy Catalyst

3.5.3. Hydride System Study

a. Introduction

The hydride system study was carried out at SNL. The following describes some of the parameters involved in the design and manufacture of a hydrogen storage system, based on metal hydrides. The purpose is to supply hydrogen to a 10 kW (electric) fuel cell in a fixed site location for up to 72 hours of continuous operation. Assuming an overall fuel cell efficiency of 50%, the total stored hydrogen energy required is 1440 kWh. On a lower heating value basis (LHV) of 120 MJ/kg, this corresponds to 14.4 kg of hydrogen per 24 hour period, or a total of 43.2 kg for 72 hours. For such large quantities of hydrogen, it is worthwhile to consider modular construction for the storage system because module weight and size would be more manageable for fabrication and transport to the operating site. In addition, any possible failure would not result in the total loss of the stored hydrogen or of the storage capacity.

b. Weight and Volume of Storage Systems

Estimates of the size and weight of storage systems using various hydrides have been made and are summarized in the following graphs and discussion. The assumptions built into the estimates and their rationalization are also discussed. To first order, the volume density of hydrogen in hydrides of practical value are roughly equal. Furthermore, the packing density of these materials in storage beds is generally about the same in order to accommodate volume expansion during the hydriding phase. Containment and heat exchange methods are also not significantly dependent on the specific material. Therefore for this initial study, only one volume was estimated for all of the hydride materials considered in this study. The overall volume for a hydride storage system as a function of operating time for the 10 kW application is shown in Figure 3-7.

Figure 3-7. Hydride System Volumes

The volume of an equivalent pressurized gas system at 3600 psi is also shown for comparison. The pressurized gas system volume was assumed to require about 10% additional volume over the compressed gas volume. This would account for containment, mounting and plumbing of multiple cylinders; however, a gas compressor unit (not required for the hydride system) was not included. There is an approximate factor of three difference in volume between the two approaches as shown.

The weight density of hydrogen is a strong function of the particular hydride material. For the purposes of these estimates, hydrides were classed into the following weight and compositional categories: AB5, AB, magnesium alloys, and a new material, catalyzed sodium-aluminum. The AB5 and AB categories correspond to the well known low temperature alloys based either on rare earths and nickel (AB5) or binary combinations of hydride and nonhydride forming elements (AB). They are generally available from commercial suppliers and contain additional elements which modify their properties, such as operating temperature and pressure, for specific applications. However, weight densities are not significantly different between specific alloys and are assumed, for this preliminary estimate, to be either 1.5 wt.% for the AB5 alloys and 1.8 wt.% for the AB alloys.

The SNL research with magnesium alloys has shown that weight densities in alloys, which have improved temperature-pressure characteristics over pure magnesium (7.6 wt.%) generally lie in the range of 3.5 to 4 wt.%. A level of 3.8 wt.% (Mg_2Ni) was used in the present estimates. There is an additional consideration for these alloys; they operate at a relatively high temperature (approximately 150–200°C), for PEM fuel cells. Two different approaches were considered. In the first case, it was assumed that no waste heat from the fuel cell was used, so that additional hydrogen was needed to provide the dissociation energy. In the second case, it was assumed that the waste heat temperature could be increased to the required hydride operating temperature so that no additional hydrogen were required. However, no estimates for the weight or volume increment for this device were made.

Recently, favorable results in the literature have been reported on new hydride system, a catalyzed sodium-aluminum hydride, that suggest probable hydrogen weight densities of 4 to 5 wt.% with an operating temperature of about 150°C. This material option is included in our estimates; however, details of the process are lacking so that system requirements were simply assumed to be the same

as the current hydrides. In addition, this material may require a special approach to effectively utilize the fuel cell waste heat. Although this material is still in the early research phase, it was included in our study to evaluate its impact on the design.

A summary of estimated weights for storage systems using the various hydrides discussed above is shown in the Figure 3-8.

Figure 3-8. Hydride System Weights

It was assumed in these estimates that aggressive engineering designs were used to minimize overall weights. Prior hydride beds have typically not addressed this issue, but design estimates and small demonstration units have indicated that systems can be built at the weights shown in the figure. Note that the additional weight with the heavier hydrides becomes increasingly more significant with increasing operating time. A system built with an AB alloy would have a total weight of about three metric tons to provide for 72 hours of backup power, while a magnesium alloy system would weigh about a metric ton less, even without utilizing the waste heat from the fuel cell.

Current pressurized gas containers that are used for large quantities of hydrogen, such as tube tanks, typically use low cost steels and are fairly robust, resulting in weight fractions comparable to the heavier hydride systems. Advanced composite tanks which are currently available are somewhat better than the lowest weight hydrides considered. As pointed out previously, a compressor unit would likely be needed for this option unless tanks were replaced and filled elsewhere. Liquefied hydrogen storage was not considered for this application because boil-off losses would be too great over extended periods of time.

c. Design Options

It is clear from Figure 3-8 that weight is an important factor in fabricating the storage system. Modular construction has some advantages over single unit construction. For the case of a magnesium alloy with no heat input, six 12 hour modules could be used. Each module would weigh approximately 360 kg, or 794 lb. This size unit is much easier to fabricate, test, transport and install than a single unit weighing over 4700 lb. Other advantages of modular construction include a smaller hydrogen release in the event of a containment failure; a single internal failure of a modular unit is less costly than the loss of a larger assembly. The modular approach also provides some flexibility in satisfying customer needs. Individual customers could choose longer or shorter projected operating times, with only one basic unit being assembled, and the configuration of the storage system could be altered to accommodate specific space considerations. The major disadvantage of modular design is the additional plumbing and packaging required. This results in slightly higher costs and also an increase in overall volume.

The design of a heat exchange system to integrate the fuel cell waste heat with the hydride is an important consideration. For low temperature units, polymers could be used effectively in the coolant loop to reduce cost and weight. Furthermore, the heat exchange assembly need not be part of the welded hydride-containing assembly as is typical of current designs.

Refueling can be accomplished through demountable units which are filled at another site, or by filling in place. The best choice may be dependent on specific site, fuel availability, etc. Demountable units would require the use of dependable reusable fittings to ensure that connections remain leak tight. The weight of the units are likely to be a strong argument against using this approach. The hydride system weight for 72 hours of backup is seen to be very large in Figure 3-8. As mentioned earlier, hydride units can be filled in place at relatively low pressures and do not require a compressor unit.

d. Cost Estimates

The cost figures shown in Table 3-3 should be considered as preliminary estimates since Sandia has little experience in fabricating the units described above. Only two of the hydride options were evaluated - the AB alloy, which is readily available and somewhat better in weight performance than the AB5 material, and the magnesium alloy without heat input. Costs are estimated for small production quantities (α units), larger production quantities (β units) and for low cost hydride materials. Both AB and magnesium alloys have been fabricated at low cost and it is believed that the \$5/kg cost estimate used in the calculations is achievable in the near future. Structural material estimates are based on current seamless stainless steel costs. Welded materials, which may be used in some parts of the system, are factors of two or more lower in cost. However, they are not recommended for use in the hydride assemblies. Estimates were not made for the catalyzed sodium-aluminum hydride because of the limited experience with this material. However, raw material costs are relatively low, suggesting that \$5/kg may also be a reasonable long term estimate for this case as well. The AB5 alloys at the present time cost at least as much as the AB materials and offer no particular advantage over the other hydrides.

Table 3-3. Hydride Economics			
	Small Quantity (α units)	Large Quantity (β units)	Low Cost Hydride
AB Hydride	\$60.0K	\$48.0K	\$12.0K

Structural	\$ 8.4K	\$ 7.2K	\$ 7.2K	\$ 7.2K
Labor	\$ 8.0K	\$ 8.0K	\$ 8.0K	\$ 8.0K
Total	\$76.4K	\$63.2K		\$27.2K
Mg Hydride	\$37.0K	\$23.0K		\$ 7.6K
Structural	\$ 9.1K	\$ 7.8K	\$ 7.8K	\$ 7.8K
Labor	\$ 8.0K	\$ 8.0K	\$ 8.0K	\$ 8.0K
Total	\$54.1K	\$38.8K		\$23.4K
Note: K denotes thousands.				

e. Safety Issues

Hydride systems for energy storage applications are generally low pressure devices. They are normally designed for operating in the range of 1 - 10 atmosphere pressure over the expected ambient and operating temperature range. In this respect, they offer an advantage over pressurized systems by eliminating PV energy concerns and reducing hydrogen/material compatibility problems significantly. Refueling also takes place at low pressures, eliminating the need for maintenance and inspection of compressor units. Hydride properties are such that they are stable and gas release is self-limiting; that is, heat must be supplied to the hydride in order for hydrogen to be released. In the absence of heat, the temperature of the material and therefore the hydrogen release rate will both get smaller until a steady state is reached between heat absorption from the environment and heat loss from hydrogen desorption. In the case of an external fire, sufficient heat can be supplied to severely over-pressurize the containment vessel. Pressure relief valves are typically employed to vent the over-pressure gas.

Some hydride materials, when they are in the activated state required for hydrogen absorption, can be pyrophoric to some extent when exposed to air. For fixed site applications, accidental breakage of the containers is an unlikely event. However, incompatibility between some hydride alloys and some container materials could give rise to holes or cracks, releasing hydrogen and admitting air. The specific alloys and their containment systems must be evaluated for compatibility and for their response in the event of air exposure from leakage or a catastrophic event.

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