

***Low Cost, High Efficiency Reversible  
Fuel Cell Systems***

Phase III Final Report  
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## 1. Executive Summary

Technology Management, Inc. (TMI) has completed and successfully met the milestones of a 3-phase study of systems utilizing TMI's reversible solid oxide electrochemical stack technology. The work, started in March 2000, included laboratory demonstrations of reversible stacks and subassemblies, engineering of complete conceptual systems, including an advanced hydrogen refueling stations which could accelerate the growth of a national *distributed* hydrogen supply infrastructure, and cost studies of operation.

The various studies focused on common design objectives -- low cost, high efficiency, and minimized emissions -- and were consistent with TMI's commercial focus: compact, modular, distributed systems at the residential to small commercial scale operating on either natural gas or propane fuel. Uses included renewable applications integrated with wind or photovoltaic power as optional input energy sources, and systems capable of multiple outputs, such as AC power, recovered heat, and compressed hydrogen. Also considered were more traditional backup or supplemental power applications to ensure continuous power availability during outages by generating electricity from stored hydrogen.

Component research on reversible cells and small stacks also met all technical targets. The work included examination of seal leakage rates, area specific resistance, and degradation rates. Cells and stacks were operated reversibly as both fuel cells and electrolyzers. A complete stack hot subassembly was designed, built, and demonstrated on natural gas, with excellent electrochemical efficiency.

At the systems level, conceptual designs, engineering calculations, and cost studies were completed showing the cost of producing pure hydrogen -- up to 40 MPa (5800 psi) for vehicles -- at as low as \$1.65. per kg (or 2.0 cents/mile). This calculation, which is lower than known alternatives, assumed natural gas at \$10.00 per mcf and achievement of certain operating and maintenance (O&M) expense forecasts.

Over the course of the study, increased interest by DOE in hydrogen generation and infrastructure projects for distributed generation encouraged TMI to show how the reversible components could be incorporated into a refilling station for hydrogen vehicles which could produce hydrogen on demand while minimizing the importance of hydrogen storage. The station employs a tandem configuration -- operating the technology in forward (fuel cell) mode to produce electricity and in reverse (electrolyzer) mode to produce hydrogen. Preliminary calculations show that this system configuration can serve continuous electrical demands and intermittent hydrogen demands at competitive economic performance.

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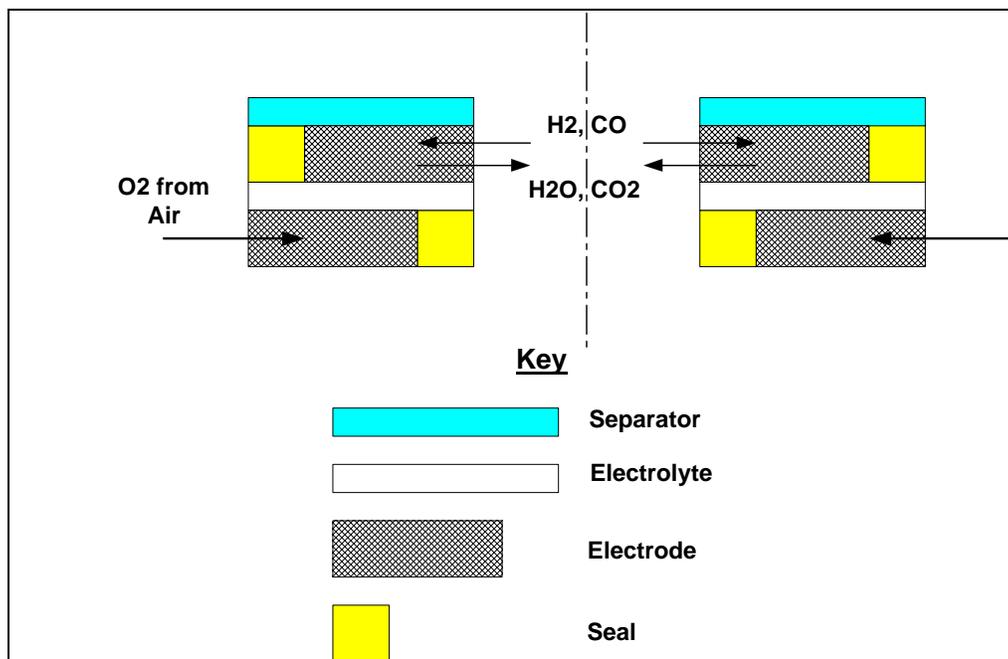
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## 2. Introduction

This final report summarizes a 3-phase program performed from March 2000 through September 2003 with a particular focus on Phase III. The overall program studied TMI's reversible solid oxide stack, system concepts, and potential applications. The TMI reversible (fuel cell – electrolyzer) system employs a stack of high temperature solid-oxide electrochemical cells to produce either electricity (from a fuel and air or oxygen) or hydrogen (from water and supplied electricity). An atmospheric pressure fuel cell system operates on natural gas (or other carbon-containing fuel) and air. A high-pressure reversible electrolyzer system is used to make high-pressure hydrogen and oxygen from water and when desired, operates in reverse to generate electricity from these gases. Figure 1 is a schematic (not to scale) of TMI's proprietary reversible cell concept.

**Figure 1. TMI Reversible Solid Oxide Cell**  
(traverse cross section)



The cell is shown operating in fuel cell mode on a carbonaceous fuel gas mixture and air. The reacting gases diffuse into the porous electrodes, which are relatively thick with small radial dimensions. The oxidation products diffuse out of the fuel electrode. The cells can also operate in the reverse (electrolysis) direction. The impact of this novel fuel cell design is to reduce the complexity of auxiliary equipment used in the balance of plant compared to designs based on conventional fuel cell designs. Calculations have shown

that the proposed systems also have the potential for achieving higher efficiencies in both fuel cell and electrolysis modes than existing alternatives.

Housed inside a pressure vessel, the stacks can be operated at high pressures. This allows the reversible stacks to be used in a variety of modes: dedicated fuel cell modules (at atmospheric pressure with air), dedicated electrolyzer modules (at high pressure), or in two-way reversible electrolyzers (capable of performing both hydrogen production and energy storage and using high pressure).

Consistent with TMI's commercial focus, the more detailed investigations were on compact, modular, distributed systems at the residential to small commercial scale operating on either natural gas or propane fuel, including a vehicle hydrogen refilling station as an example of a small commercial business.

### 3. Phase I and II Review

#### 3.1 Phase I (March through September 2000) Review

Phase I concentrated on concept and cost studies, with limited experimental work.<sup>[1]</sup>

##### *Cost Studies and Economic Evaluation*

Grid-independent, residential scale electric power systems using the proposed reversible fuel cell/electrolyzer technology were compared with systems using conventional technologies. Propane fuel was assumed, with wind power an optional supplement. The proposed systems store excess renewable power by operating stacks in electrolysis mode and storing hydrogen. Power is generated in fuel cell mode from either stored hydrogen or propane. Conventional systems were assumed to use large banks of deep cycle batteries and an engine-generator. Projected cost and emissions savings are summarized in Table 1 (power cost includes capital amortization, maintenance, and fuel).

**Table 1. Phase One Studies**

System Type	Installed Cost	Power Cost cents/kWh	Annual CO <sub>2</sub> tons
Engine-Generator	\$22,900	83	9.8
Wind + Engine-Generator	\$33,900	76	2.4
TMI Fuel Cell	<b>\$5,500</b>	<b>17</b>	2.5
Wind + TMI Fuel Cell	\$24,900	49	0.7
Wind + TMI Reversible Fuel Cell	\$18,200	30	<b>0.7</b>

The above projections will vary based on assumptions. For instance, if natural gas were used, all of the above costs would be lower. Substitution of the wind system used in the example with a comparable solar photovoltaic system would increase the costs. Other considerations were that solar and wind equipment costs may decline as industry volumes reach mature levels, whereas engine-generator technology is already mature. Grid independent power is typically much more expensive today than utility power, but the latter is not always available or preferred.

A total of ten reversible cells were tested under conditions simulating the temperature and gas composition in a reversible system. The cell area specific resistance (ASR) was found to be slightly lower in electrolysis mode than in fuel cell mode, thus confirming the feasibility of operating reversibly. One cell was operated over 2400 hours.

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[1] "Proceedings of the 2000 Hydrogen Program Review," NREL/CP 570-28890

### 3.2 Phase II (February 2001 through April 2002) Review

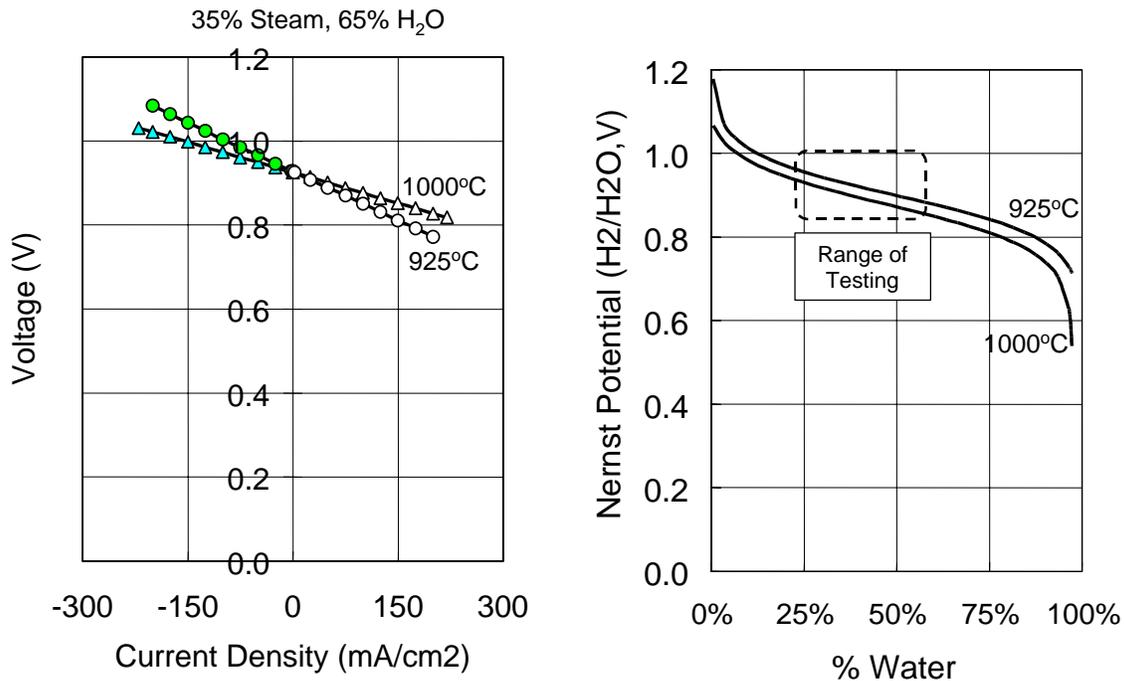
Phase II expanded the Phase I effort and included laboratory development work as well as cost and engineering studies.<sup>[2]</sup>

#### Cell and Stack Development

Improvements were made to existing TMI cell and stack test equipment to widen the range of reversible cell and stack testing conditions. Development work was then performed on reversible cells and stacks, with emphasis on fabricating thicker electrodes and seals for diffusion style cells. Testing was performed using both forced flow and diffusion flow geometries. Figure 2 shows a typical reversible cell operating in both fuel cell (positive current) and electrolysis (negative current) modes with 65% H<sub>2</sub>/35% H<sub>2</sub>O. The absence of a discontinuity at zero current indicates that no significant activation polarization exists in these cells. Notably, the figure shows that electrolysis at practical current densities requires voltages far lower than needed by PEM electrolyzers (typically close to 2.0 V).

Diffusion type (see Fig. 1) single cells and stacks up to five cells were tested in both fuel cell and electrolysis modes. A five-cell stack was operated for over 1000 hours continuously. Notwithstanding slight seal leakages detected in most runs, performance approached predicted values. Higher observed rates of degradation than for TMI's forced flow cells were attributed to the leakage.

Figure 2. Reversible Cell Polarization



[2]"Proceedings of the 2002 US DOE Hydrogen Program Review," NREL/CP 610-32405

### **Engineering and Cost Studies**

During Phase I, the cost of electricity and environmental advantages of grid independent residential installations were studied. Initial projections showed the costs per kWh were relatively high even using advanced fuel cell technology. The systems studied in Phase I, however, viewed the production of hydrogen as an energy storage medium only and not as a potential fuel in complementary or combined systems and applications. During Phase II, a more advanced alternative system was studied using the same reversible stack technology but including more options such as using natural gas (or propane) plus potentially renewable electric power from wind, photovoltaic, and/or the grid to feed these advanced systems. The output of the advanced systems was further expanded to produce high-pressure vehicle grade hydrogen, as well as AC power and usable heat.

With the combined benefits of a lower cost fuel (natural gas), higher capacity factors, and production of valuable co-products (hydrogen and recovered heat), the projected cost of electricity is lower than the Phase I cases. Table 2 shows example cost calculations. Natural gas, used to produce any combination of AC and hydrogen, results in the same unit costs. The base case example projected an AC power cost of 4.5 cents per kWh and a hydrogen cost of 2.0 cents per mile: both lower than expected alternatives. There are also major environmental advantages.

**Table 2. Costs and Efficiency Comparisons**

<b>Parameter</b>	<b>DOE Goal</b>	<b>TMI Projection*</b>
Pressurized H <sub>2</sub> at refueling station from fossil fuels	\$12-15/MM BTU	\$14.26
Renewable-based H <sub>2</sub> production	\$10-15/MM BTU	\$14.41
Electrolyzer cost	< \$300./kW	\$265.
Electrolyzer efficiency	> 92%	95%

\*using \$5.00/mcf natural gas cost, 2 cents/kWh renewable power cost and other assumptions

Since each parameter in the table above varies directly with the assumptions used, sensitivity effects may be obtained using proportions. For example, both fuel cost and thermal credit vary directly with natural gas price. Annual capital cost is proportional to annual capital charges rate and installed cost.

## **4. Phase III Summary of Results**

### **4.1 Objectives**

Based on learnings from earlier work, the objectives of Phase III were to:

- Improve performance of reversible solid-oxide stacks (capable of operating in both fuel cell and electrolysis modes) by reducing polarization and rate of degradation.
- Demonstrate an integrated fuel cell hot subassembly operating with a stack of about 50 reversible type cells using natural gas fuel.
- Evaluate the economic impact of reversible solid oxide fuel cell/electrolyzer systems and consider applications where a competitive advantage may be achieved.

### **4.2 Technical Approach**

Prior work showed cell performance in electrolysis mode superior to fuel cell mode. Therefore, Phase III testing concentrated on fuel cell mode (with both hydrogen and natural gas fuels and air as the oxidant). Acceptable cell performance depends on many factors including gas crossover (i.e., seal leakage), gaseous diffusion polarization, electrical contacts between cell layers, temperature, fuel composition, and cell fabrication details. All factors were considered in cell performance development. Testing focused on single cells, small (2-5 cell) stacks, and larger stacks (between 10 and 30 cells).

The hot subassembly design, based on prior TMI designs, was operated on very low air supply pressure (a few inches of water column) to enable the use of a low-pressure blower. Provisions were included for both hydrogen and natural gas fuels.

### **4.3 Tasks and Milestones**

The test plan began on May 1<sup>st</sup>, 2002 and continued through October 31<sup>st</sup>, 2003, under the following five tasks:

#### **Task 1: Cell Development**

The following quantitative cell performance targets were established.

- Area Specific Resistance (ASR) < 1.00 Ohm-cm<sup>2</sup>
- Voltage Degradation < 5% per 1000 hours
- Seal C<sub>v</sub> < 10<sup>-5</sup>

#### **Task 2: Cell and Stack Fabrication**

Several hundred cells were fabricated for Phase III.

#### **Task 3: Hot Subassembly Demonstration**

A hot subassembly capable of testing large stacks on hydrogen or natural gas fuel plus air was designed, built, installed, and commissioned. The assembly included stack mounting assembly, startup electric heater, heat exchanger, thermal and electric insulation, fuel feed subsystem, stack clamping assembly, sensors, and enclosure.

#### Task 4: Engineering and Cost Calculations

Conceptual equipment configurations and flowsheets were proposed. Detailed material and energy balances were computed, including electrochemical calculations. Itemized cost calculations were made for installed capital and operating costs, based on selected assumptions.

#### Task 5: Reporting

Planned reports include a presentation at the annual peer review meeting (Berkeley, April 2003), annual public summary, and this final report.

Proposed milestones were:

- (Month 6) First 50-cell stack test
- (Month 9) Performance targets met in 5-cell stack
- (Month 12) Performance targets met in 50-cell stack

Because of changes in the preferred geometry, the large stack test was changed from a 50 cell stack to a 30 cell stack. Thirty cells were the largest stacks that could safely fit in the hot subassembly fabricated in Task 3.

## 5. Results: Cell Development

The following sections describe workplan tasks (out of sequence to reflect the logical progression of cell development).

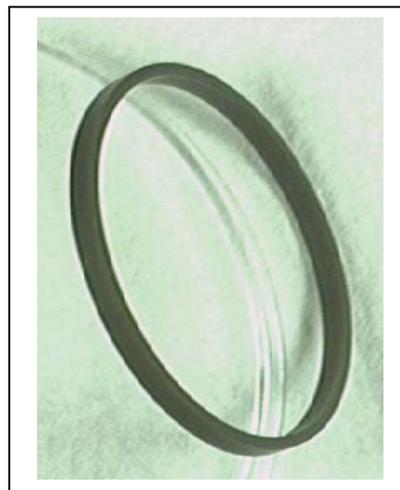
### **5.1 Cell and Stack Fabrication (Task 2)**

The majority of cells used in Phase III were of the TMI reversible design (Fig. 1). Evolutionary improvements of all components occurred during this phase. As mentioned before, increases in the preferred electrode thickness resulted in a reduced maximum cell count for a given stack height. Approximately 300 cells were produced and tested for Phase III.

**Figure 3. Reversible Cell Cathode Seal.**

### **5.2 Sealing (Task 1.3)**

Good sealing of both seals in every cell is required to achieve high cell voltage and efficiency, minimize electrode damage from reactant crossover, and enable low degradation rates. TMI adopted the valve coefficient,  $C_v$ , as a quantitative measure of seal leakage. An orifice (or leak) with a  $C_v$  of 1.0 will yield a flow of 1 gallon of water per minute at a pressure difference of 1 psi. Formulas are available for computing  $C_v$  from gas flows at any temperature and pressure. Cell simulations have shown that each seal should have a  $C_v$  below about  $10^{-5}$  for minimal performance loss. Figure 3 shows an example of a typical cathode seal for the reversible cell design.



Leakage measurements were performed on cells at operating temperature using either air or hydrogen, depending on the seal being examined. In extreme cases,  $C_v$ 's were found to be unmeasurable, being either too small (below the lower detection limit of about  $10^{-8}$ ) or too large to permit cell pressurization for testing (higher than  $10^{-3}$ ). Such extremes do not require quantification, since one is negligible and other is unusable. Because of the inability to separate contributions, individual seals were tested in half-cell tests. Table 3 shows the best results achieved.

**Table 3.  $C_v$  Measurements on Seals**

Seal	Optimized Measured $C_v$
Anode	$10^{-7}$ to $10^{-8}$
Cathode	$4.0 \times 10^{-7}$

Experiments indicated that a rough correlation existed between cell open circuit voltage (OCV) on dry hydrogen fuel and seal  $C_v$ . Above about  $5 \times 10^{-5}$ , the impact of  $C_v$  on OCV was very small. Observations also indicated that when  $C_v$  was very small (good), open voltage varied little when fuel flow rate was altered.

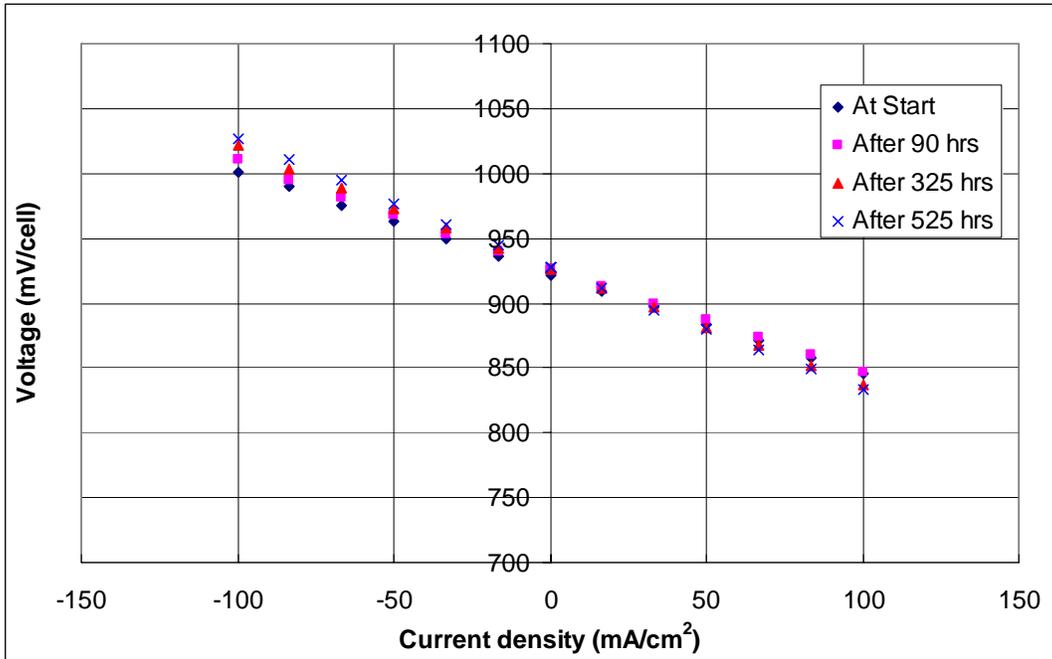
### **5.3 Polarization and ASR (Task 1.1)**

Polarization of a cell refers to its drop in voltage relative to the gas phase potential as current increases. TMI has repeatedly demonstrated that its cells have negligible activation polarization. The measured polarization is therefore treated as the sum of concentration polarization and Area Specific Resistance (ASR) polarization. Concentration polarization is computed with respect to the fuel and oxidizer compositions in the adjacent manifolds. These calculations include the effects of gaseous diffusion between the manifolds and the electrochemical reaction sites at or near the electrode-electrolyte interfaces. ASR polarization is the sum of ohmic resistance and charge-transfer effects through the cell thickness (including contact resistances) and is expressed as  $\text{Ohm-cm}^2$ . Both concentration and ASR polarization tend to increase roughly linearly with current at a fixed fuel flow rate. Resolving observed polarization into two discrete components is difficult. Therefore, TMI developed finite-difference cell simulation models to separate the observed results into specific polarization components. The models were calibrated using a variety of supplemental measurements on cell components, other types of cells, etc., and include the calculation of fuel surface thermodynamic activity.

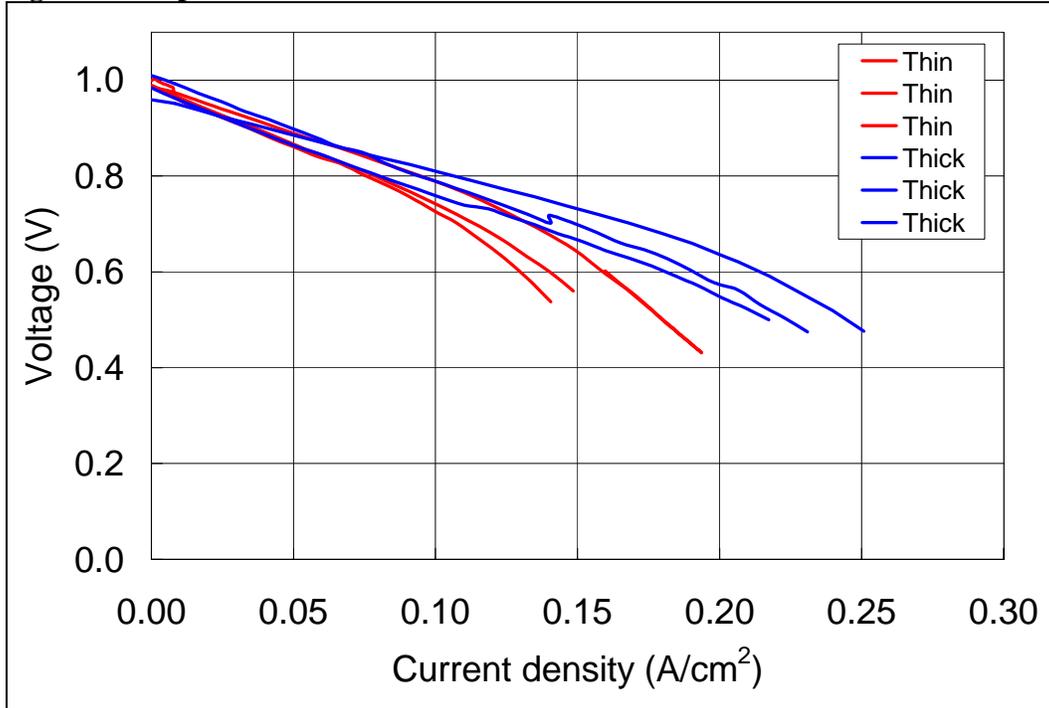
The observed ASR values were unexpectedly high in early studies. Therefore, alternate anode and cathode materials were evaluated to improve current exchange with emphasis on catalytic dopants (and counter ions for mixed oxides). An example cell using alternate cathodes operating reversibly is shown in Figure 4. After several iterations, the target Phase III ASR target of  $1.00 \text{ Ohm-cm}^2$  was demonstrated repeatedly on both cells and stacks.

During Phase III, concentration polarization was found to limit performance at higher current densities. Bulk cathode thickness, in particular, was found to impact cell performance as shown in Figure 5. Increased electrode thickness and adjusted cell geometry and construction methods (to reduce shrinkage during operation) dramatically reduced the impact of the diffusional limits for practical cell embodiments. As seal leakage, electrode dimensional stability, and assembly details improved, ASR values at higher currents eventually approached those found in TMI's conventional forced-flow cells.

**Figure 4. Reversible Three Cell Stack with Alternate Cathode**  
(900°C, 65% H<sub>2</sub> / 35% H<sub>2</sub>O)



**Figure 5. Impact of Cathode Thickness on Cell Performance for Passive Cells.**

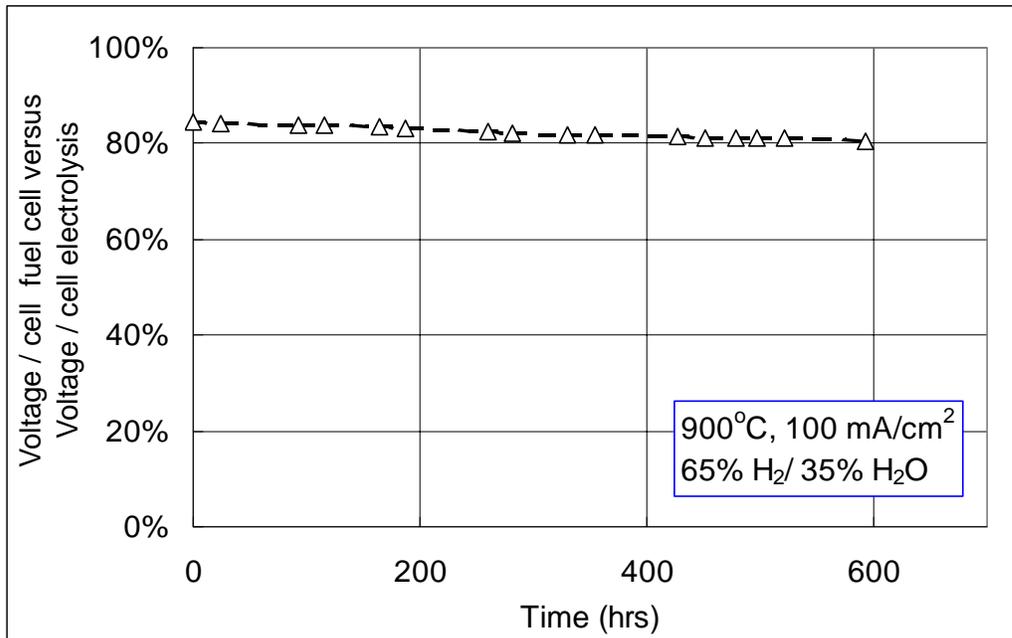


### **5.4 Degradation Rate (Task 1.2)**

Degradation is the time dependent decay in performance of a stack or system at otherwise constant conditions. Degradation can be broadly categorized as steady state or acute. Steady state degradation generally occurs because of temperature-dependent diffusional phenomena. The most common forms are oxide scale growth, dopant segregation, sintering, and interface passivation / delamination. Acute degradation is more often associated with change in condition (such as a thermal cycle) that can result in component breakage or other failure. During this program, TMI focused on steady state degradation mechanisms.

Since most steady state degradation mechanisms are thermally activated, a major area of focus was on reduced temperature operation. As shown in figure 2 above, early work was performed at 925°C to 1000°C. Advanced cathode development led to a reduction in average temperature to below 900°C while actually increasing performance. As another example, Figure 6 shows the reversible efficiency of a 3-cell stack operating at 100 mA/cm<sup>2</sup>. In this case, the y-axis shows the ratio of the voltages in fuel cell to electrolysis voltage. This ratio would be essentially double the steady state degradation of a system running in fuel cell mode and is the most severe evaluation criteria.

**Figure 6. Reversible Degradation Rate of a 3-Cell Stack.**

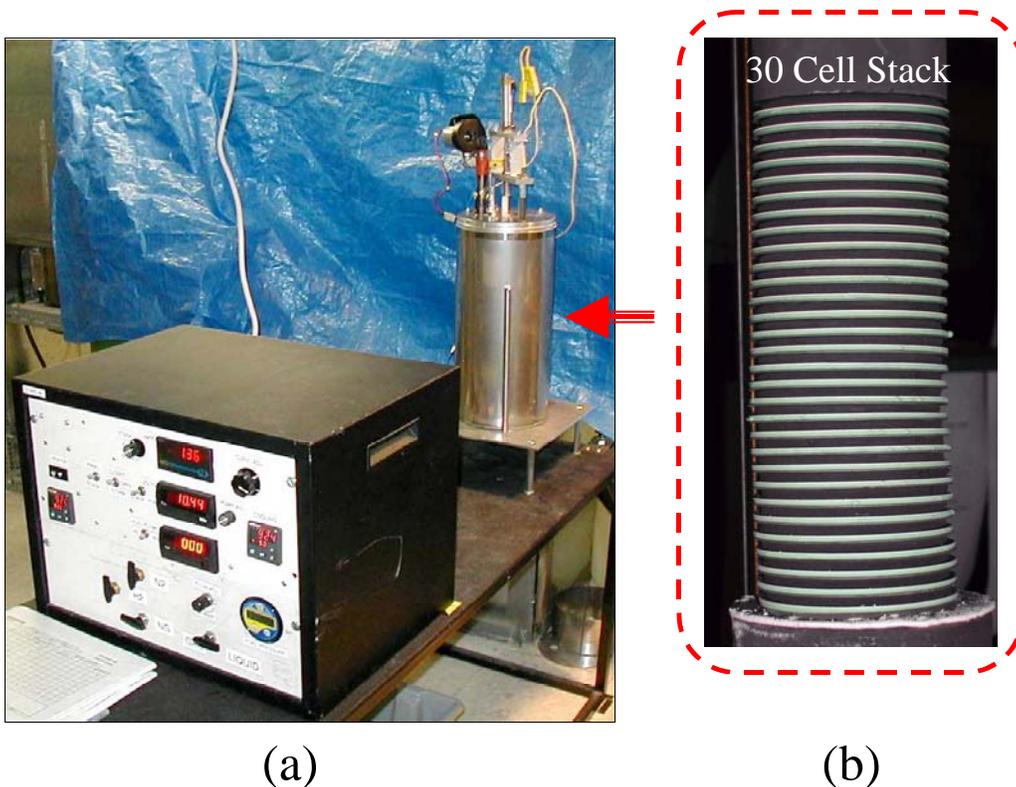


## 6. Results: Demonstration System

### 6.1 Equipment Construction (Tasks 3.1 and 3.2)

A demonstration system was designed, built, installed, and operated for a series of runs using reversible cell stacks. The system consists of two subassemblies: a hot subassembly and an auxiliary equipment enclosure (Figure 7). The system was designed to test large stacks using either natural gas or hydrogen fuel. Based on the optimized cathode, the maximum practical cell count was 30 cells. Figure 7(b) shows a 30-cell stack after testing.

**Figure 7. Reversible Stack Demonstration System**



The hot subassembly (back-right of photo) includes an insulated enclosure, electric heater, sensors, stack mounting assembly, fuel inlet assembly, heat exchanger, stack clamping assembly, sensors, air blower, and connections for fluids and electrical.

The auxiliary equipment enclosure includes meters, temperature controllers, valves for fuel gas components (natural gas, hydrogen, and startup nitrogen), flow controls, regulated active electrical load circuit, circuit breaker, switches, and custom control circuits. A connection is provided to a data logging system. Multiple safety features are included.

### **6.2 System Testing and Demonstration (Task 3.3)**

The first run of a complete system was on February 6, 2003. Multiple tests were run for early troubleshooting. The final program demonstrations began in September 2003. Table 4 shows a brief summary of five of the tests including the final two using the preferred cell geometries (runs 30S-177-017 and 30S-172-190). Table 4 shows the maximum electrochemical efficiency achieved for these runs. Higher power densities were also demonstrated repeatedly but at the expense of efficiency.

**Table 4. Maximum Efficiency Large Stack Testing on Natural Gas or Methane**

Stack ID	Cell Count	LHV Efficiency	mW/cm <sup>2</sup>
20S165-033*	20	51.9%	50
10S-172-175	10	38.5%	67
10S-172-178	10	46.3%	80
30S-177-017	30	53.6%	73
30S-172-190	30	54.2%	74

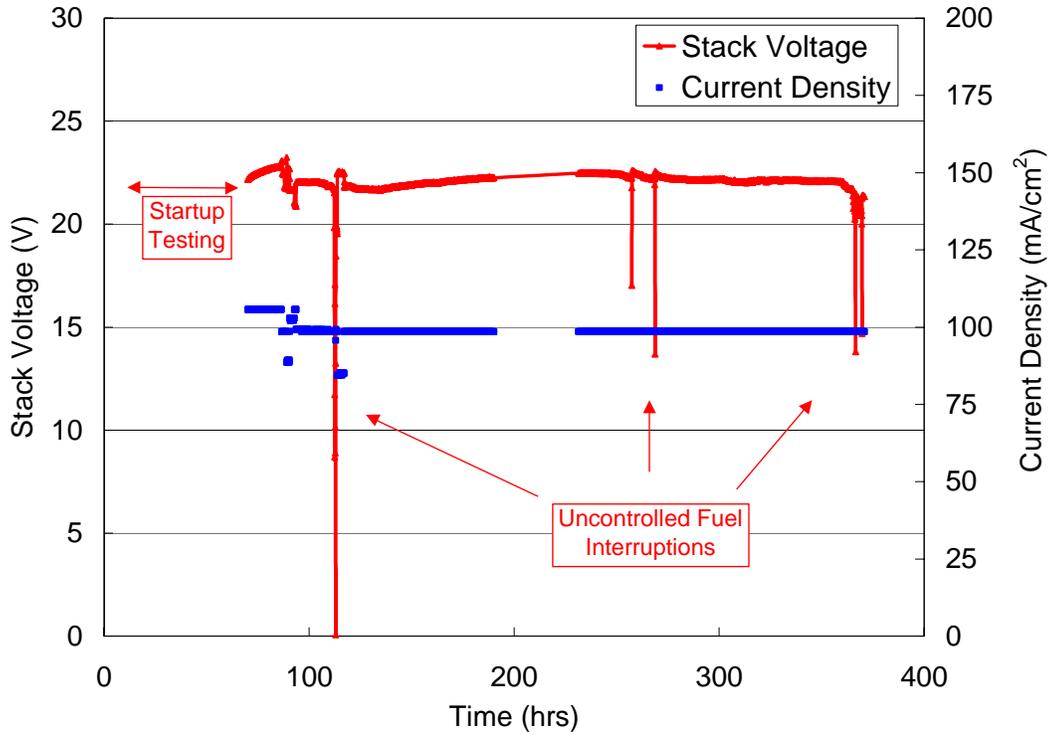
\* Tested in non-integrated reactor

Figure 8 shows the voltage and current response of stack 30S-172-190 running in steady state for approximately 300 hours. The stack performance was very stable over this time period. Malfunctions in the fuel mass-flow controller caused uncontrolled gas cycling in closed circuit. The first several interruptions were recovered without major stack damage but eventually, a cluster of controller failures caused permanent damage. The test is ongoing as of the date of this report, with a total test time in excess of 500 hours.

### **6.3 Electrolysis Testing (Task 3.3)**

The original program specifications did not call for electrolysis testing on large stacks, however, because of the exceptional performance achieved by the 30 cell stacks on natural gas, TMI decided to expand the scope of the testing to include electrolysis evaluations. The equipment was modified to include water injection and an electrolysis electrical circuit. The results of the water-hydrogen electrolysis for one stack are summarized in Table 5. These tests are only electrochemical tests of the cells and stack package in particular and do not include the entire energy balance (this particular system does not have thermal storage). Overall, the results were consistent with small stack testing.

**Figure 8. Durability of a 30-Cell Stack with Passive Operation on Natural Gas.**



**Table 5. Electrolysis Testing on a 30-cell Passive Stack**

Volts	Amps	Water ml/min	Watts	H2O Utilization	mA/cm2	mV/cell	Polarization mV/cell
30.80	2.00	0.67	61.6	50.2%	142	1027	119
32.60	2.50	0.67	81.5	62.7%	178	1087	179
34.40	3.00	0.67	103.2	75.2%	214	1147	239
36.50	3.25	0.67	118.6	81.5%	231	1217	309
38.80	3.50	0.67	135.8	87.8%	249	1293	386
40.60	3.70	0.67	150.2	92.8%	263	1353	446
41.80	3.80	0.67	158.8	95.3%	270	1393	486
38.90	3.80	0.75	147.8	85.1%	270	1297	389
40.20	4.00	0.75	160.8	89.6%	285	1340	432
42.70	4.20	0.75	179.3	94.1%	299	1423	516
43.00	4.30	0.75	184.9	96.3%	306	1433	526

## **7. Results: Engineering and Cost Studies (Task 4)**

TMI performed numerous technical and cost studies on alternative methods for producing high purity hydrogen at 400 bar (5800 psi) pressure for emerging fuel cell vehicles such as cars, light trucks, and SUVs. The example TMI system below was selected as the most attractive possibility amongst those studied.

### **7.1 Base Case Hydrogen Production System**

The following installation, scaled for a residence, produces 1.0 kg of hydrogen per day, sufficient for operating two vehicles each achieving 82 miles/kg for 15,000 miles per year. Vehicle refilling could occur as often as nightly from the storage tank included. The system would consume natural gas, 200 Watts of electric power (e.g. produced from an adjacent TMI natural gas fuel cell system also supplying power to the residence for example), purified water, and ambient air and output hydrogen and clean 200°C exhaust.

#### **7.1.1 Cost Projections**

A cost study of this system assumed a future natural gas price of \$10.00 per thousand cubic feet. The residence was assumed to already have an installed TMI fuel cell system with heat recovery to which the hydrogen production system would be added. The following results were obtained.

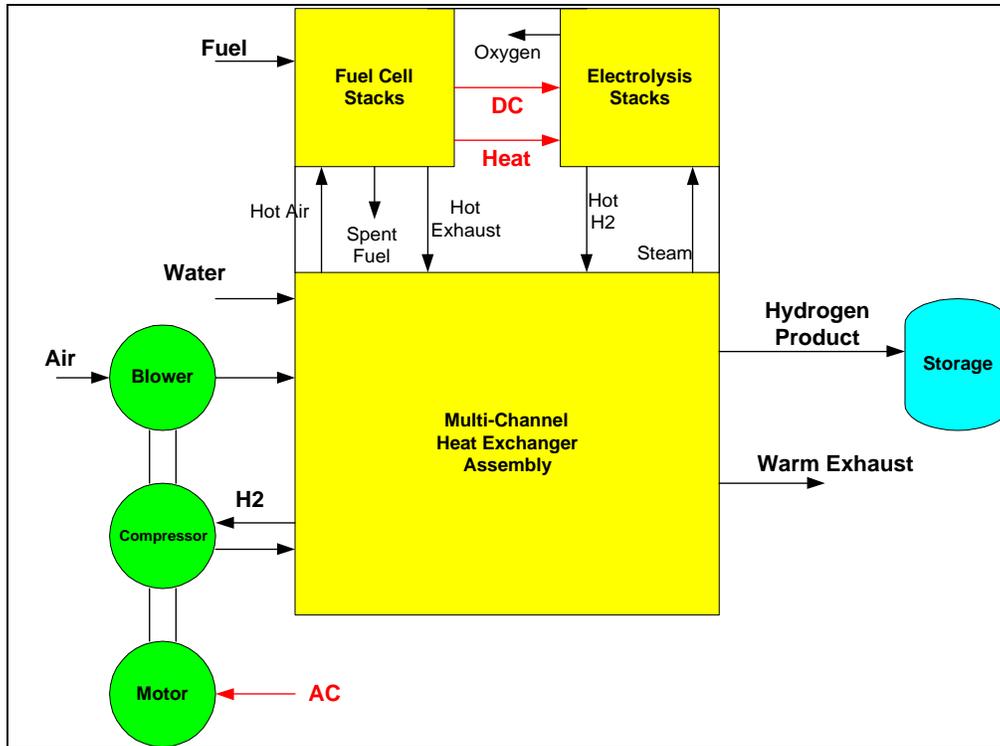
Installed Equipment Cost:	\$2800.
Natural Gas Cost:	\$1.18 per kg hydrogen
Maintenance Cost:	<u>\$0.47</u>
Sum:	\$1.65 per kg hydrogen (2.0 cents/mile)

The above costs assume recovery of surplus heat for hot water and seasonal space heating and quantity manufacturing of the equipment. "Sum" is the total operating and maintenance (O&M) cost. As the calculations indicate, the proposed system produces hydrogen at a competitive cost of \$1.65/kg.

#### **7.1.2 System Description**

Figure 9, is a simplified schematic of the proposed system, scaleable for one, two, or more hydrogen vehicles. The projected energy efficiency of hydrogen production (hydrogen higher heating value/natural gas lower heating value, including fuel for the required electric power input) is about 85%. The projected average annual efficiency including heat recovery is 103% of lower heating value (93% of higher heating value).

**Figure 9. Simplified System Schematic for a Reversible Residential System with Vehicular Hydrogen Generation.**



An efficient miniature compressor would employ four stages, with intercooling, precooling, and aftercooling. The required air inlet pressure is quite low (under 1 kPa or 4 inches of water), thus requiring a very small and quiet blower. By operating the solid oxide electrolysis cells below 1.1 Volts / cell, outstanding conversion efficiency is projected. This requires 1.) surplus heat from the fuel cell stacks to supply thermal energy for electrolysis, 2.) very high expected efficiency of the TMI fuel cell stacks, 3.) high degree of thermal integration, and 4.) moderate electric power input.

The system would use no flames and emit no  $\text{NO}_x$ , CO, particulates, organics, or odors.  $\text{SO}_2$  emissions are expected to be only a few parts per billion. The extremely clean exhaust may be used for supplemental humidification of the residence during cold weather if desired. Fossil  $\text{CO}_2$  emissions would be lower than other methods using fossil fuel due to the exceptionally high system efficiency.

The paragraphs below discuss possible variants to the base case system.

## **7.2. Vehicle Filling Stations**

Larger versions of the proposed systems could be installed at retail filling stations to manufacture hydrogen for retail motorist markets. The projected costs would likely be

lower than for the smaller system. For example, commercial buyers of natural gas usually pay lower rates. The averaging of demand among many customers could permit a higher annual capacity factor for hydrogen production.

Using natural gas fuel at \$6.70 per thousand cubic feet, preliminary cost projections for hydrogen are \$1.53 per kg and AC power output at 3.6 cents / kWh, assuming economies of scale.

On the minus side, filling stations are not likely to utilize all available surplus heat and would need to charge considerably more than the residential costs cited above to cover labor, overhead, capital recovery, and profit. Road taxes are expected to eventually be the same for both cases. In spite of higher costs, filling stations or its equivalent will be necessary to serve travelers and those without access to home systems. Possible alternative fuels for filling stations are discussed below.

### **7.3. Biofuel Alternative**

The proposed systems would operate on either hydrocarbon fuels (e.g., natural gas, propane, gasoline, kerosene, or diesel) or bio-liquids (e.g., ethanol, bio-methanol, bio-diesel). While biofuels have the added advantage of producing no fossil CO<sub>2</sub>, since they are renewable (recycling CO<sub>2</sub> from the atmosphere), they are not as available as fossil fuels, which are the lowest in cost. Natural gas has superior convenience, moderate cost, and minimum fossil CO<sub>2</sub> emissions compared with other hydrocarbons.

An example filling station system producing up to 500 kg of hydrogen per 24 hours would be sufficient to furnish 4 kg to 125 cars per day. In AC power mode, the same system could produce up to 1000 kW of electric power. Systems could be scaled larger or smaller as needed. Using soybean oil fuel at 16 cents per pound, preliminary total cost projections give (40 MPa, pure) hydrogen at \$1.92 per kg and (3-phase 480 or 208V) AC power at 4.5 cents per kWh (with no tax credits).

### **7.4. Use of Photovoltaic or Wind Power**

When and where available, photovoltaic or wind power could be used to reduce fuel consumption in the proposed hydrogen production equipment. The example system would require zero fuel with an electric power input of 1900 Watts.

### **7.5. Grid Connection**

The proposed systems can be modified to produce a mix of outputs (e.g. electric power at some times and hydrogen at other times), a feature which could be managed to match pricing tariffs. For instance, under certain circumstances, night rates may make power purchase lower in cost than local use of fuels. The example system would be managed to produce 2200 Watts of electrical output and no hydrogen. Adding modules would increase installed capacity if significant power sales were expected.

### **7.6. Energy Storage**

If stored hydrogen were used as fuel for the on-site TMI fuel cell system, the combined system would function as a “hydrogen-air battery”. Energy storage mode becomes attractive when grid sales are not an option, when excess photovoltaic or wind energy is available, and when heat recovery is practiced (thereby improving “round trip” storage efficiencies to nearly 100%).

### **7.7. Other Variations**

Numerous alternatives (for producing vehicle hydrogen) to the systems described have been considered and many cost studies performed. In principle, solid oxide electrolyzers could also be operated at high pressures using a high-pressure water pump and thus avoid the need for a compressor (and its power). However, the need for a very high pressure insulated vessel would be a challenge. The use of thermochemical compression, if developed, would be a more elegant and less expensive solution.

Various on board hydrogen storage alternatives are being actively considered at this time by product developers, including higher gas pressures. This requirement can also be met by the proposed configuration at slightly higher capital and operating cost.

## 8. Conclusions

A summary of the milestones achieved during this phased, 3-year program by Technology Management, Inc. would include the following:

- Demonstrated TMI's novel reversible fuel cell design
- Built, tested, and refined electrochemical cells and stacks operating in fuel cell and electrolysis modes
- Designed, built, and tested a 30-cell stack test system
- Demonstrated 30-cell stack with per cell performance levels comparable with small stack and theoretical calculations.
- Completed the following engineering cost studies:
  - Stand-alone residential system with hydrogen storage.
  - Integrated co-generation system.
  - Residential / small commercial size integrated system with hydrogen generation for vehicles.

This phase demonstrated that: scale-up to reasonable stack sizes is feasible, performance can match or exceed forced-flow SOFC levels by carefully controlling component geometry, and degradation can be mitigated by materials substitution and reduced temperature.

Overall, this program demonstrated that solid oxide based fuel cell-electrolyzer systems can serve as an important 'bridge' technology between the hydrocarbon-based centralized power generation systems of today and the vision of a distributed hydrogen economy of tomorrow.

## **9. Recommendations for Future Work**

Additional technology demonstrations are essential, as are additional engineering studies. Only through such testing and calculations can the benefits of the technology progress toward public benefit. In addition, further demonstration of feasibility will highlight the novel operation of the high-temperature passive fuel cell/electrolyzer, a consistent source of confusion for innovative developers.

The current technology, while successful in a laboratory environment, needs additional development to meet more demanding commercial performance criteria. Electrode stability for long term operation appears promising but needs further evaluation, in more aggressive conditions. The power density of a final system may also need to be increased depending on the application. Though thermal integration has been demonstrated as being viable for increasing electrolysis efficiency, a thermally integrated demonstration system needs to be engineered and built. Hydrogen generation has been demonstrated repeatedly but hydrogen has not been formally captured and analyzed for possible trace impurities. Finally, larger scale demonstration systems must be operated to identify other scale-up issues.

Finally, largely as a result of the phased, iterative structure of the program and renewed interest in hydrogen, an unexpected business opportunity has emerged which should be given further attention. This opportunity is a vehicular hydrogen fueling stations where the primary feedstock is a renewable biomass fuel. Biomass liquids are easily transportable and, when combined with TMI's own commercial value proposition for certain markets requiring a modular, pollution free system, with flexibility for expansion, reliability, and ease of maintenance, create an opportunity for early adoption. The TMI design could enable the distributed production of hydrogen at individual refueling stations at costs competitive to gasoline.