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AN ASSESSMENT OF THE STATUS OF FUEL CELL/BATTERY VEHICLE POWER SYSTEMS

WILLIAM J.D. ESCHER AND RICHARD W. FOSTER

MASTER

February 1980

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ABSTRACT

An assessment of the status of the integrated fuel cell/battery power system concept for electric vehicle propulsion is reported. The fuel cell, operating on hydrogen or methanol (indirectly), acts as a very high capacity "energy battery" for vehicle sustaining operation, while a special "power battery" provides over-capacity transient power on demand, being recharged by the fuel cell, e.g., during cruising.

A focused literature search and a set of industrial and Government contacts were carried out to establish views, outlooks, and general status concerning the concept. It is evident that, although vehicle battery R&D is being actively pursued, little of today's fuel cell work is directed to transportation usage. Only very limited attention has been, and is being, given to the fuel cell/battery power system concept itself.

However, judging largely from computer-simulated driving cycle results, the concept can provide needed range capabilities and general operating flexibility to electric vehicles. New transportation applications, conventionally viewed as beyond the capability of electric vehicles, may thereby be practical, e.g., rail, trucks.

In view of these potential and important benefits, and the absence of any comprehensive research, development, and demonstration activities which are supportive of the fuel cell/battery system concept, the initiation of an appropriate effort is recommended by the Assessment Team. This general recommendation is supported by applicable findings, observations, and conclusions.

GLOSSARY

ANL	Argonne National Laboratory
BNL	Brookhaven National Laboratory
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ERDA	U.S. Energy Research and Development Administration (now absorbed into DOE)
EV	Electric Vehicle
IGT	Institute of Gas Technology
LASL	Los Alamos Scientific Laboratory, University of California
LLL	Lawrence Livermore Laboratory, University of California
MERADCOM	Mobility Equipment Research and Development Command, U.S. Army, located at Fort Belvoir, Virginia
RD&D	Research, Development, and Demonstration
SNG	Substitute Natural Gas
SPE	Solid Polymer Electrolyte
STOR	Division of Energy Storage Systems (DOE)
TVA	Tennessee Valley Authority

FOREWORD

Hydrogen-air fuel cells, coupled with storage batteries, offer a promising option which would permit electric vehicles to out-perform current battery-powered vehicles. The purpose of this report is to assess the status of the fuel cell/battery approach for efficiently utilizing our abundant and renewable resources in the transportation sector--particularly for automobiles. This use of fuel, in the form of hydrogen, and derived from water using coal, solar, hydro, wind, and geothermal primary energy resources, is highly desirable because it would reduce our dependence on petroleum-based fuels. Moving off oil dependency is a primary goal of the U.S. Department of Energy (DOE). Specifically, the goal of the Division of Energy Storage Systems (STOR) in the DOE is to assess and develop promising fuel storage systems which conserve petroleum.

Unlike batteries, fuel cells have their supply of fuel stored in a separate container which can be sized for range--just as gasoline tanks are. The fuel cell can indirectly use abundant or renewable resources by reacting hydrogen gas and the oxygen in air to produce electrical energy (and water) for propulsion. Thus hydrogen serves as an energy carrier. As stated, hydrogen can be made from water, via electrolysis, using electrical energy produced from renewable primary energy sources. Alternatively, the hydrogen can be made from coal-derived methanol, which is processed to yield hydrogen on-board the vehicle.

The potential improvement in vehicle performance over conventional battery vehicles is based on use of the fuel cells for range, and the batteries for power surges. A flywheel system could also be considered for supplying surge power. With this mode of load sharing, each device can be optimized for its role in the propulsion system. During periods of light load, the batteries are recharged by the fuel cells using fuel carried on-board. Furthermore, in comparison with the internal combustion engine (ICE), the fuel cell offers substantial energy conservation because its overall efficiency is two to three times that of the ICE.

A related study program supported by DOE/STOR, and conducted by the Lawrence Livermore Laboratory (LLL), deals with a comparison of candidate energy storage systems for automobile propulsion. Here, various batteries,

the fuel cell/battery, flywheels, hydrogen-powered engines, and hybrid systems are considered in computer-modeled automobiles of various sizes and performance capabilities. Results of the study show that the optimistic projections made for the fuel cell/battery system generally compare favorably with those made for alternative systems. The present report assessing status of the fuel cell/battery system was conducted as part of the LLL study activity under its Chemical Energy Storage Panel. The effort was conducted under subcontract to Brookhaven National Laboratory (BNL).

From this assessment report, it is evident that the fuel cell is a potential key to developing our abundant and renewable resources for fueling automobiles--and perhaps for trucks, buses, and trains. An appropriate avenue for initiating work on this new concept exists in Public Law 94-413, "The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976," because fuel cells, along with batteries, are within its scope.

Gerald Strickland (BNL), Chairman
Chemical Energy Storage Panel
LLL Program on Energy Storage Systems
for Automobile Propulsion

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AN ASSESSMENT OF THE STATUS OF FUEL CELL/BATTERY VEHICLE POWER SYSTEMS

EXECUTIVE SUMMARY

A. MOVING TRANSPORTATION OFF OIL - THE GOAL

Because the transportation sector consumes about 55% of all petroleum used in the United States, and about half of that is being imported at increasingly higher prices, it is imperative to find ways of reducing our dependence on imported oil. The consequences of the nation's dependency on oil imports to satisfy the demand for petroleum-based fuels and products have been a source of major concern from a political, economic, social and technological perspective. To help offset these concerns, the Department of Energy has assigned a high priority to technology development activities which place emphasis on: (1) identification and implementation of fuel alternatives which would be derived from our coal supply or from renewable resources; and, (2) development of the electric vehicle. The merits of either or both of these strategies can be enhanced by including parallel approaches which will allow additional market penetration and are consistent with the goal of effectively moving transportation off oil. This report provides an assessment on the status of, and a rationale for, a complementary strategy--development of the automotive fuel cell/battery power system.

B. THE COMPREHENSIVE MERITS OF ALTERNATIVE OR COMPLEMENTARY STRATEGIES

The automotive fuel cell offers the promise of embodying the best features of the fuel and electric traction-power alternatives, while overriding their negative features. It is recognized that fuels derived from coal or renewable resources will be costly in the near term--especially if utilized in conventional internal combustion engines, which operate at efficiencies as low as 10% over representative driving cycles. Fuel cell systems can use similar fuels and provide energy conversion efficiencies two to three times that of internal combustion engines. Electric vehicles, even those utilizing advanced state-of-the-art batteries, will depend on off-peak charge rates to approach cost competitiveness; and they presently require long recharge times and have poor performance (range/acceleration), due to low energy and power densities

of the batteries. Fuel-cell systems can be refueled in times that compare favorably with conventional automotive refueling practice; and they can be effectively integrated with storage batteries to provide performance profiles similar to those of conventional vehicles.

C. THE AUTOMOTIVE FUEL-CELL/BATTERY CONCEPT

The fuel cell has enjoyed substantial support for aerospace power applications, for electric-utility power generation, and as a gas-utility co-generation option in both the public and private sectors. However, automotive use of the fuel cell is a relatively new energy-conversion option which has virtually been ignored. This inactivity has been based on concerns regarding fuel supply and storage, as well as on the high unit costs due to the use of noble-metal catalysts in the electrode components. Recent advances in fuel supply/storage technology, and in electrocatalysis, may do much to eliminate or alleviate these concerns. This assessment was undertaken to evaluate the current status of the fuel cell/battery power system--mainly for the automobile.

Fuel cells comprise electrochemical systems which undergo oxidation/reduction reactions at catalyzed electrodes, and utilize appropriate electrolytes for ion transport, just as batteries do. Unlike batteries, fuel cells have a separate fuel container which can be sized for an appropriate range. The fuel may be in the form of pure hydrogen, or a suitable hydrocarbon such as methyl alcohol which can easily be reformed on-board to yield hydrogen plus inerts. Air (oxygen) is the oxidant. In the hydrogen-oxygen reaction at the electrodes, electrical energy is generated along with water; thus the fuel cell is environmentally desirable.

Operating at high efficiency, the fuel cell can be designed for electric power consistent with cruise requirements. Higher power demands for acceleration or hill climbing can be accommodated by combining the fuel cell with a low-storage-capacity/high-power battery subsystem. This battery can be charged during the cruise cycle, thus minimizing the possibility of life-degrading deep discharges.

Clearly, the automotive fuel cell augmented by a power battery can utilize technology being developed for alternative fuels; and, owing to its electrical output, ties in well with advances in electric motors, drive trains and other ancillaries being developed specifically for battery-powered electric

vehicles. Alternative fuels would be used more effectively because of the higher conversion efficiency of the fuel cell compared with the internal combustion engine. Rapid refueling and performance characteristics could be achieved consistent with user practices in the automotive sector.

D. SUMMARY STATUS OF FUEL-CELL RD&D

In the vehicle propulsion context, the thrust of industrial and Government support has been directed toward development of the storage battery rather than the fuel cell. Intensive efforts are being made under the impetus of "The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976 (Public Law 94-413)." Near-term, fleet-size battery vehicle demonstrations are emphasized, and there has been no implementation of system development for the automotive fuel cell. However, the Public Law specifies the development of fuel-cell propulsion systems as an additional or complementary activity.

The automotive industry maintains an awareness of fuel-cell technology, but is not involved in RD&D efforts for readying this technology's application to current or future needs. The minimal activities in automotive fuel-cell development appear to persist, notwithstanding the significant and encouraging contributions of Dr. Karl Kordesch of Union Carbide. Dr. Kordesch demonstrated a converted compact car (Austin A-40) powered by an alkaline fuel cell, which ran on compressed hydrogen at ranges and speeds consistent with highway driving practices (see Appendix A).

Small-scale development and testing activities are ongoing at U.S. Army Mobility Equipment Research and Development Command (MERADCOM), Los Alamos Scientific Laboratory and Brookhaven National Laboratory. A current study by Lawrence Livermore Laboratory (LLL), "Energy Storage Systems for Automotive Propulsion," compares computer-modeled automobiles powered by internal combustion engines, by an alkaline fuel cell/battery system, by batteries alone, or by hybrids. This assessment was conducted as part of the LLL study, for the Chemical Energy Storage Panel, under funding supplied by the Division of Energy Storage Systems in the DOE.

E. COMPARATIVE POWER-SYSTEM AND FUEL COSTS

Current fuel-cell technology suggests system production costs in the range of \$150-\$250/kW (1979\$). These costs contrast markedly with \$10/kW for internal combustion systems and \$50/kW for diesel systems--both of which have

been highly developed over the years. It is conceivable that future automotive fuel cells will become cost competitive, especially with focus placed on the development of electrodes which do not require noble-metal catalysts. Furthermore, fuel-cell fabrication does not require the high-precision machining which is essential to engines, thus reinforcing the probability of attaining the cost-reduction goals.

Fuel-cell cost projections must remain speculative due to the absence of a concerted effort in estimating production costs which would factor-in potential advances in the technology. For example, noble metals would not be required in advanced-alkaline fuel cells. Progress in hydrogen storage and hydrogen separation/purification, combined with on-board hydrocarbon or alcohol fuel reprocessing, can provide pure hydrogen (CO/CO_2 free) to the fuel cell--a requisite for effective performance of alkaline fuel cells. The tie-in of these synergistic developments bodes well for future cost-competitive, efficient, and clean vehicle power-system alternatives.

Fuel costs, considering only hydrogen and methanol as the most likely candidates, are expected to be a major cost element. Hydrogen can be made available by water electrolysis at costs below \$20/million Btu, depending upon capital and operating costs of electrolysis, the principal one being the cost of electricity. Coal-derived hydrogen and methanol can be produced at lower costs ranging from an estimated \$8-\$15/million Btu.

Comparable gasoline cost (untaxed) at the refinery is estimated at \$6/million Btu (\$0.75/gallon). Giving due consideration to the improved energy conversion efficiencies of fuel cells over that of the internal combustion engine, the cost disparities that currently exist can be largely eliminated. In addition, the more rapid cost escalation, as oil resources diminish, will make alternative non-petroleum fuels even more attractive.

Consideration must be given to the added costs associated with penetration of the energy infrastructure by hydrogen and methanol. This aspect must be addressed in order to assign a high degree of credibility to the automotive fuel-cell option.

F. POTENTIAL OF THE FUEL CELL/BATTERY SYSTEM

Integration of the fuel cell and battery represents a technological extension of advances currently pursued for automotive propulsion systems. This combination can provide broader capabilities over battery systems such as:

more flexible over-the-road performance; extended driving ranges; rapid recharging; and no need for recharging from an electric-utility grid.

The modularity of the fuel cell/battery system permits consideration of traction applications beyond passenger vehicles and vans. It can be used in special-purpose, pollution-free vehicles such as fork-lift trucks, mine vehicles, as well as in vital trucks, inter-city buses, and rail systems.

G. RECOMMENDATIONS

- o Initiate a focused research, development and demonstration program. emphasizing the development of low-cost automotive fuel-cell systems.
- o Provide for strong Federal support at the outset with an incrementally increasing role to be assumed by industry as the technology matures. The program could, under present statutes, be supported in the initial stages, under DOE's Public Law 94-413 program.

SECTION 1

INTRODUCTION AND SUMMARY

A. TECHNICAL CONCEPT AND RATIONALE

A fuel cell/battery power system, as applied to vehicle propulsion, is an integrated electric drive system in which:

- Sustaining power, as required for vehicle cruising, derives from fuel cells supplied by onboard chemical fuels, and
- Transient power needs, beyond those for which the fuel cells are rated, are provided by a high-power-output storage battery, which is recharged by the fuel cells.

Usually, in such a system, the storage battery is recharged on the vehicle from the fuel cell as needed and whenever fuel cell power demand is less than its rated capacity. The fuel cell itself is operated on hydrogen fuel, supplied as such directly, or produced aboard from hydrocarbon or alcohol fuels via a "fuel processor." (Note: hydrazine and ammonia can be used as fuels also; hydrazine directly in the fuel cell.)

In this system concept, the electric vehicle (EV) is chemically fueled rather than being electrically charged from a utility grid. This leads to a much shorter "charging time" than is presently the case with battery electric vehicles.

Figure 1-1 shows schematically, in two levels of detail, the functional makeup, and the component interfacing within, a fuel cell/battery vehicle.¹ Although these diagrams are meant to be largely self-explanatory, a comment on one component,* the "fuel processor" (the upper diagram) or "reformer" (lower diagram), is necessary.

Fuel cells developed to date consume hydrogen as fuel directly, using the oxygen from air (or as directly supplied in some cases). Electrical energy is produced and water is formed as the reaction product. Where a hydrogen-containing fuel is used, rather than hydrogen itself,

* If required. (Not required if hydrogen fuel is supplied.)

More detailed system diagram.

Figure 1-1. Fuel Cell/Battery Vehicle Power System Functional Schematic Diagrams¹

such as a liquid hydrocarbon or an alcohol, it must be first "processed" before it is usable in the fuel cell. Typically, in such cases, a hydrogen-containing gaseous product is produced from a liquid fuel. Steam reforming is an exemplary process; hence, the inclusion of a "reformer" in Figure 1-1 (lower sketch). In such systems carbon dioxide and other constituents, along with water, comprise the exhaust.

Why integrate the fuel cell and the battery in a common vehicle power system? This question is pertinent since, to date, electric vehicle systems which have been developed and demonstrated have been mainly based on fuel cells, or much more extensively, batteries alone.

The reasons for considering this approach are:

1. A typical vehicle driving cycle requires only occasional high power output to meet transient demands (e.g., accelerations); most of the time — and for the bulk of the vehicle's energy expenditure — much lower power demands occur (e.g, sustained cruising conditions).
2. While selected batteries are effective producers of high power levels (to meet high but limited duration transient demand), they are limited in terms of total energy which can be supplied on a single charging (of relatively long duration, i.e., several hours).
3. A battery type and design that is best for meeting limited high power transients is ordinarily not optimal at storing maximum energy amounts. (In all-battery systems as is later discussed, this situation has led to the development of hybrid or dual battery/battery systems which integrate two different battery types: a "power battery" and an "energy battery.")
4. Fuel cells, which can be viewed functionally as a special kind of "energy battery," are quite superior to any battery in that their electrical energy generation capacity is limited only by the amount of onboard fuel supply.
5. On the other hand, the "power battery" remains a more effective means of meeting the limited, high transient energy demands than the alternative of sizing-up the fuel cell complement to meet these requirements (for cost, weight, volume, and complexity reasons).
6. Thus, the integration of the two "best" elements — "power battery" and the "energy fuel cell" — is seen as a logical option.

The basic complementary nature of the fuel cell and the battery can best be illustrated on a "Ragone Plot." This is a presentation of prime mover specific power (W/kg) versus prime mover specific energy (Wh/kg). In this instance, "prime mover" is meant to comprise both the

motive power device (e.g., heat engine, electric motor) and the fully fueled/charged energy storage unit (e.g., fuel tank, storage battery).

Such a plot is presented on a log/log basis in Figure 1-2. On it, three types of prime movers are reflected:

1. Heat engines (3 types), as curved quasi-horizontal curves in the upper right-hand area
2. Batteries (5 types), as downward curving lines in the lower-left and center of the plot
3. Fuel cells (2 types), as nearly horizontal lines in the lower center of the plot.

Both current technology (solid lines) and a projected technology (dashed lines) are shown for the three categories.

Interpreting the plots, one can observe:

1. Heat engines, vis-à-vis batteries, have (1) a much higher specific power and (2) unlike batteries, an essentially unlimited specific energy (horizontal vs. near-vertical nature of the corresponding curves).
2. Fuel cells, vis-à-vis batteries, have roughly equivalent specific power, but — like heat engines — are essentially unlimited in specific energy.
3. Fuel cells, vis-à-vis heat engines, have an approximate order-of-magnitude lower specific power, but share the quasi-unlimited specific energy feature. Further, fuel cells provide for superior energy conversion efficiency as indicated by the lower slope (i.e., the more nearly horizontal trend) of their characteristic curves.

One can nominally conclude that:

1. Heat engines can, in a single prime-mover type, provide high levels of specific power and specific energy (their adequacy is testified to by the extremely widespread, nearly exclusive, use of heat engines for transportation system motive power).
2. Neither the fuel cell by itself (lacks specific power, hence leads to a more massive installation than the heat engines for equivalent power capability), nor the battery by itself (lacks specific energy, hence leads to a limited range [endurance] system as compared with the heat engine) can deliver the combined power and energy output achievable with heat engines.
3. The integration of the fuel cell (sized to a given energy, or range/endurance requirement) and the battery (sized along with the additive fuel cell contribution to a given power requirement) into an optimal system offers the potential for achieving an acceptably equivalent performance characteristic of the heat engine.

4. The superior energy conversion efficiency of the fuel cell provides the potential, in an optimal fuel cell/battery power system (Item 3, above), of lower specific energy (fuel) consumption in a transportation vehicle.

This, then, is the general rationale for current interest in the fuel cell/battery transportation power system as a potential new system which should be developed and deployed in appropriate vehicle systems.

There are also other important technical reasons for integrating the fuel cell and the battery, with reference mainly to considering either one alone, as the prime mover. Among these reasons are:

- a. Long life and stable performance characteristics have been demonstrated with fuel cells, so that vehicle performance will not degrade, either over a driving cycle or over the life of the vehicle.
- b. Long battery life can be achieved under the shallow discharge/charge cycling anticipated in fuel cell/battery system operation (in contrast to deep, life-shortening cycling in conventional electric battery vehicle cycling).
- c. The battery facilitates fuel cell system start-up and can prevent fuel cell voltage reversals (an undesirable characteristic of straight fuel cell power systems).

B. TECHNICAL AND PROGRAM STATUS OF TRANSPORTATION FUEL CELLS AND BATTERIES

Substantial improvements have been made in both fuel cell and battery technology during the last decade. However, whereas a focused programmatic thrust has been mounted to advance transportation battery development for all-battery vehicle applications, such is not the case for transportation fuel cells.

Rather, by comparison, only low-level funding has been allocated to transportation fuel cell development in comparison with that being spent on large electric and gas utility fuel cell systems, and space and military power generation applications. Although some of the non-vehicle power system fuel cell projects provide direct benefits to potential transportation applications, much of this work is believed to be largely inapplicable to transportation, e.g., molten carbonate fuel cells.

Tables 1-1 and 1-2 summarize technology advances for both fuel cells (generally) and batteries (transportation oriented). Whereas directed

Figure 1-2. Ragone Plots for Batteries, Fuel Cells, and Various Heat Engines (Source: Brookhaven National Laboratory)

Table 1-1. IMPROVEMENTS IN H₂/AIR FUEL CELLS

	Alkaline		Acid			SPE	
	1967	1977	1967	1977	1977	1967	1977
Current Density (mA/cm ²)	100	200	300	300	400	15-42	700
Cell Voltage (V)	0.75	0.7	0.55	0.65	0.6	0.6-0.7	0.68
Power Density (mW/cm ²)	75	140	165	195	240	10.5-25	476
Operating Temperature (°C)	65-75	80	160	190	25	25	100
Thermal Efficiency (%)	51	47	3.7	44	41	40	46
Catalyst Loading (mg/cm ²)	1	<0.2	20	0.75	4	65	8
Start-Up Time	3.5 hours	5 min. (1969)			15 min.	3 hours	1 min.
Life (hours)	5000			>12,000	600	1000	40,000

Source: Reference 1.

Table 1-2. BATTERY FUNDING SHOWING PORTION ALLOCATED TO EV BATTERIES (\$10⁶)

	FY 1979			FY 1980		
	Total Batteries	Near-Term Batteries	Advanced EV Batteries	Total Batteries	Near-Term Batteries	Advanced EV Batteries
Near-Term Batteries	6.33	6.33	--	9.95	9.95	--
Advanced Batteries	11.50	--	8.53	14.40	--	10.75
Scalar Applications	0.80	--	--	5.00	--	--
Electrochemical System Research	2.50	--	1.63	2.60	--	1.63
Supporting Research	2.14	0.38	0.42	3.00	0.83	0.59
Electrolytic Technology	1.32	--	--	1.50	--	--
Dispersed Battery Applications	<u>5.90</u>	<u>--</u>	<u>--</u>	<u>4.50</u>	<u>--</u>	<u>--</u>
	30.49	6.71	10.58	40.95	10.78	12.97

Note: "Total Batteries" column include program elements, e.g., component technologies efforts, other than what is represented; hence the columns do not add up horizontally.

Source: Reference 2.

Table 1-2, Cont. PERFORMANCE PROJECTIONS FOR NEAR-TERM BATTERY PROGRAM

	Lead-Acid				Nickel/Iron				Nickel/Zinc			
	1979*	1980	1982	1984	1979*	1980	1982	1984	1979*	1980	1982	1984
Specific Energy (Wh/kg)	34	42	50	50	48	54	58	60	60	64	67	70
Specific Power (Wh/kg)												
-- Peak (20 seconds @ 50% State of Charge)	80	90	95	100	100	110	120	120	110	140	140	140
--Sustained (1/2 hour rate)	35	40	45	50	70	80	90	95	80	80	90	95
Cells/Modules Cycle Anticipated Life Capability (No. Cycles)	300	300	500	750	800	1500	1800	2000	100	200	300	500
Production Capacity Per Contractor (Batteries/Year)	200	400	1100	2000	50	100	300	500	40	100	100	500
Battery Price @ the Above Production Level (\$/kWhr)(1979\$)	100	100	80	60	1200	500	350	300	550	500	500	250

* Only cell data will be obtained in 1979. Table values are estimates for batteries if assembled with these cells.

Source: Reference 2.

funding for program support is also indicated for the ongoing battery work in the table, none is shown for the fuel cell for reasons stated.

Not presented in Tables 1-1 and 1-2, but as will be discussed later in the report, cost estimates for such fuel cell systems, assuming production volumes, are in the \$150 to \$250/kW range.

The significance of the technical and cost advances for fuel cells and batteries, reflected in this discussion, is that these gains are likely to be favorably compounded in the context of integrated vehicle power systems. Hence, it is surmised that a "new look" on a comparative basis with alternative systems could show substantial gains for the fuel cell/battery system relative to the competition.

C. BACKGROUND AND STATUS OF FUEL CELL/BATTERY VEHICLE POWER SYSTEMS ACTIVITIES

A limited number of experimental fuel cell/battery powered vehicle systems have been assembled and demonstrated. These include:

- Hydrazine fuel cell/nickel-cadmium battery powered motorbike, Kordesch, Union Carbide Corporation, ca. 1966.
- Hydrazine fuel cell/lead-acid battery powered automobile, Williams et al., Shell Research, Ltd. (England), ca. 1967.
- Hydrazine fuel cell/lead-acid battery powered truck, U.S. Army/Monsanto Research Corp., ca. 1968.
- Hydrogen fuel cell/lead-acid battery powered automobile, Kordesch, Union Carbide Corp., 1971-1975.
- Hydrogen fuel cell/lead-acid battery powered fork lift truck, Dowgiallo, et al., MERADCOM, 1975-1978.
- Hydrogen fuel cell/lead-acid powered golf cart, McCormick et al., LAEL, 1979.

Additionally, several straight fuel cell powered vehicle systems (no batteries) have been demonstrated including a hydrogen-oxygen fuel cell powered tractor by Allis-Chalmers Manufacturing Co. in 1959 and the hydrogen-oxygen fuel cell powered "Electrovan" project of General Motors Corporation ca. 1965.

Appendix A presents a technical review covering all but the most recent of the above listed projects in a paper by Kordesch. Further information on a number of these projects is given throughout the report.

All-battery powered vehicle systems development and demonstration activities are much more widespread, largely as a consequence of the impetus provided by the enactment of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act (Public Law No. 94-413), passed on September 17, 1976. DOE is responsible for program implementation.³ In view of the size and complexity of this program, no attempt to summarize it is included here.

A notable topical workshop on "The Fuel Cell in Transportation Applications" was held at LASL in August 1977 (Proceedings).¹ The proceedings for this meeting provide a useful and nearly-current review of the relevant state-of-the-art.

References Cited for Section 1

1. McCormick, B., et al., ed., "Proceedings of the Fuel Cell Transportation Applications Workshop," held 15-17 August 1977, Los Alamos Scientific Laboratory Conference Proceedings LA-7270-C, issued July 1978.
2. Katz, M.J., and Klunder, K.W., "The Department of Energy Electric Vehicle Battery Program: An Overview," DOE Presentation at the 14th Intersociety Energy Conversion Conference, Boston, August 5-10, 1979.
3. Anon., "Electric and Hybrid Vehicle Demonstration - 1978 ," Brochure DOE/CS-0046.

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SECTION 2

OBSERVATIONS, CONCLUSIONS, AND RECOMMENDATIONS

Based on the assessment's findings as discussed on a task-by-task basis in Section 4, this section presents the assessment team's summary observations followed by its conclusions and recommendations, both general and specific.

A. OBSERVATIONS

Status of Transportation Fuel Cell R&D

Fuel cell research and development for vehicle power systems applications is not presently being pursued at significant levels of funding, as compared with R&D support for 1) other fuel cell applications, particularly utility system use, and 2) vehicle batteries for all-battery and hybrid automotive use.

Benefits of the Fuel Cell/Battery Power System to Electric Vehicles

Based on the limited systems analyses and hardware demonstrations conducted to date, fuel cell/battery vehicle power systems appear to offer significant technical advantages and probably cost advantages over both all-battery and all-fuel cell power systems, specifically:

- Substantially extended range and endurance (and a markedly reduced battery complement) vis-à-vis all-battery systems
- Improved over-the-road performance and operating flexibility (and a reduced fuel cell complement) vis-à-vis all-fuel-cell systems
- More rapid "recharging" by virtue of fueling procedures.

Present Industry and Government Involvement

At present, in the United States, industrial and Governmental organizations are involved in fuel-cell-based vehicle power systems activities at varying, but generally low levels of effort:

- Automotive industry organizations, although "maintaining awareness," are not actively engaging in applicable RD&D.

- Fuel cell industry organizations, although active in utility and aerospace fuel cell projects, are not actively engaging in transportation-applicable fuel cell RD&D.
- The substantially funded thrust (ca. \$160 million) by the Government (DOE) in electric and hybrid vehicle RD&D (under Public Law No. 94-413), into which fuel cell vehicle applications seemingly would fit, does not presently provide support for fuel cell RD&D.
- Low-level systems analyses and limited hardware R&D in fuel cell/battery vehicle power systems is underway at MERADCOM, LASL, and BNL, the latter two organizations being supported by DOE.

Overseas Involvement

Outside the United States in the sphere of EV RD&D, fuel cell activities appear mainly absent. A focused activity is being pursued by ELENCO (see special note at the end of Section 4E), and some activities have been reported in France and Sweden.

Alternative Vehicle Applications

Stress to date has been placed on specialty vehicles applications (e.g., fork-lift trucks), and private automobile as the "target market" for fuel-cell-based power systems. However, certain other vehicle types and service applications appear to offer favorable technical opportunities and economic advantages. Hence, these transportation applications should also be vigorously pursued as fuel-cell applications: railroad systems, intercity trucks, intercity and urban buses, and short-haul and urban delivery trucks and vans.

Fuel Cell Relationship to the Electric Vehicle

In the context of all-battery electric vehicle systems, the integration of the fuel cell to achieve an optimal composite fuel cell/battery power system is anticipated as a technically and programmatically feasible step. The dual "energy battery/power battery" system, well known to the electric vehicle community, may well serve as an in-being point-of-entry for the fuel cell as a special kind of energy battery for the fuel cell as a special kind of energy battery for "second-generation" EV's.

Fuel Cell/Battery Vehicle Differences

The principal external differences between projected fuel cell/battery powered vehicles and equivalent all-battery systems will be:

- Fuel cell/battery vehicles will provide needed range extensions, faster "recharging," no performance degradation over the operating duty cycle (between fueling/charging), and will likely have rejected heat available, for compartment comfort heating.
- Fuel cell/battery vehicles will be more-or-less conventionally fueled, as opposed to being charged from the electric utility. (However, an option for providing utility hydrogen-via-electricity can be considered.)

Implications of Methanol and Hydrogen Fuels

Methanol and hydrogen as candidate fuels for fuel cell/battery vehicles have differing and far-reaching individual characteristics to be considered in any selection process:

- Methanol, being an easily handled and stored (though toxic) room-temperature liquid fuel, is generally preferred (over hydrogen) for its logistical and onboard storage advantages. Its use requires an onboard reformer with its attendant cost and operation complications (which, however, are less severe than would be the case with straight hydrocarbons) and onboard water storage. Its use essentially precludes the alkaline fuel cell (carbon oxide sensitivity problem). Also, because of possible reformer catalyst sensitivities, it may be important to specify a methanol purity level other than that of "fuel-grade" methanol.
- Hydrogen, although technically the ideal fuel, is judged a more difficult material to handle logistically, and especially, to store onboard vehicles (than methanol); its general safety aspects remain an issue of concern (particularly liquid hydrogen).

Coal as a Primary Energy Resource

Coal is viewed as a likely primary energy resource for producing hydrogen by gasification, and methanol by gasification and synthesis, using existing process technology. However, such coal-based fuel production facilities do not presently exist in the United States, with both hydrogen and methanol being derived principally from natural gas by steam reforming. The ultimate availability of coal-derived methanol and/or hydrogen is a complex issue. Involved are such factors as continuing natural gas availability, other (than fuel cell/battery vehicle) demands, the rate at which coal-mining and delivery can be expanded, and the availability of capital for constructing fuel-production facilities.

Estimated Costs of Fuels

Estimated costs for methanol from coal and hydrogen from coal were observed to be over the following ranges (Exxon Research and Engineering Co. estimates):¹

	<u>\$/10⁶ Btu (1980 \$)</u>
Methanol From Coal	7.80-14.40
Hydrogen (Gas) From Coal	7.90-9.60
Hydrogen (Liquid) From Coal	16.70-19.20

Estimated Costs for Transportation Fuel Cells and Batteries

Estimated costs for transportation fuel cells and batteries, on an assumed production-level basis, were observed in the present assessment to be:

Fuel Cells: \$150-\$250/kW
Batteries:* \$60-\$300/kWhr

(Note: See Sections 4A and B and References cited therein.)

B. CONCLUSIONS

1. At present in the United States, there is no formal comprehensive program basis for the conduct of fuel cell/battery vehicle power systems research development, and demonstration.
2. If successfully developed and introduced into vehicle fleet service, fuel cell/battery vehicles will provide substantial energy conservation benefits over competing heat engine systems because of the intrinsic high conversion efficiency of their electrochemically-based power plant. (However, it is premature to attempt to quantify such savings since these will be highly dependent on vehicle type and service, specific driving cycle, and the specifics of the power system itself.)
3. The introduction of fuel cell/battery power systems will provide a needed significant extension of range and endurance capabilities in present electric vehicles, and may substantially improve their general over-the-road performance.

* Note: Whereas the fuel cell will be priced on its power rating (kW), the battery element of a fuel cell/battery system is likely also to be priced primarily on its power rating, rather than its energy storage capacity (kWhr), as is conventional.

4. By virtue of these extended capabilities, electric power systems are likely to be competitive in a much wider range of transportation vehicle application areas than is the case at present, some of which appear to offer quite favorable RD&D and eventual market penetration opportunities.

C. RECOMMENDATIONS

General Recommendations

Based on the identified energy conservation and vehicle capabilities extension advantages of the fuel cell/battery transportation power system approach, and the present lack of a directed effort in support of this option, a focused research, development, and demonstration program element* is recommended to be initiated at the earliest practical opportunity.

If this recommendation is to be pursued, the following implementation considerations are offered:

1. It would appear that a strong Federal Government role will be mandatory in successfully launching such a program element, and a number of agencies would have obvious "charters" and capabilities for administering it, particularly DOE and DOT.
2. As an example of "placing" this recommended program element, it might well be integrated into DOE's ongoing electric and hybrid vehicle research, development and demonstration effort (mandated under Public Law No. 94-413).
3. In response to the anticipated opening up of vehicle application areas to the rail, trucking, and bus sectors (and possibly others), concerted efforts should be placed on early representation in the program element of the views and outlooks of these using sectors.
4. Finally, there will be a special need for a comprehensive, widely distributed, and appropriately updated program element planning document, as well as an active inter-organization liaison function to assist and coordinate the widespread implementation activities perceived as intrinsic to this effort.

Specific Recommendations

Within the framework of the general recommendation, the following specific recommended actions are suggested:

* Referred to as a "program element" for reasons noted in Item 2, below.

1. Mission and Systems Analysis of fuel cell/battery powered vehicles of all types of potential interest should be pursued aggressively and early. Existing computer simulation capabilities should be expanded and vigorously exercised, while needed hardware- and mission-related information is gathered (e.g., driving cycle data, servicing and maintenance constraints, and general operating environments).
2. Fuel cell and battery subsystem characteristics for designated transportation applications should be better defined; both needed general technical/cost advances and any potentially limiting technological gaps should be rapidly identified and appropriate RD&D efforts documented for implementation. All potentially applicable fuel cell types should be encompassed, as should all candidate fuels.
3. Strong fuel cell/battery systems integration efforts are required with emphasis on component matching and interfacing, and overall controller optimization. Integration with both the onboard fuel supply system and the vehicle final drive should be heavily stressed from the onset. Active feedback to the component and subsystems R&D activities should be maintained.
4. Well ahead of the formal demonstration phase, complete static laboratory and dynamic over-the-road engineering evaluation hardware systems should be constructed and operated at the earliest practical time. Such tools can initially comprise state-of-the-art components and subsystems, augmented by simulation techniques and progress to fully operable developmental vehicle systems using advanced hardware as this becomes available. Feedback to both the power systems and the component subsystem R&D efforts should be maintained.
5. Finally, in planning the demonstration phase of the fuel cell/battery system program element, it is highly recommended that the general "learning experience" of previous Federally-supported demonstration projects be very carefully heeded, e.g., the assessment by Rand.² Proceeding from this reference, as pointed out in a recent Assessment of Alternative Fuels for Intercity Trucking,³ the real purpose of the demonstration is to reduce uncertainties, of which five specific types are cited:

- "1. Technological Uncertainty: uncertainty about the feasibility of a technology for a certain use.
2. Cost Uncertainty: uncertainty about the monetary cost of manufacturing a product or operating a process or system using the technology.
3. Demand Uncertainty: uncertainty about the benefits (private or public) that will accrue from the use of the technology.
4. Institutional Uncertainty: this uncertainty dimension is divided into two categories:

- a. Internal: uncertainty about the impact of adoption on the functioning and structure of the adopting organization.
 - b. External: uncertainty about the impact of adoption on the adopting organization's relationship with other organizations such as unions or competitors.
5. Uncertainty about Externalities: uncertainty about costs and benefits that are not counted for and the price of either factor: inputs or output. This dimension includes such questions as: Is the technology or its outputs safe? Does it increase or lessen pollution, health hazards, or the like?"²

References Cited in Section 2

- 1. Cart, E.N., Jr., Carter, D.A., and Cunningham, A.R., "Alternate Energy Sources for Non-Highway Transportation," Appendixes for Volume II-B, prepared for the U.S. Department of Energy by the Exxon Research and Engineering Company under Contract No. DE-AC05-77CS05438.
- 2. Baer, W.S., Johnson, L.L., and Merrow, E.W., "Analysis of Federally Funded Demonstration Projects: Final Report," prepared for the Experimental Technology Incentives Program of the U.S. Department of Commerce by the Rand Corporation, R-1926-DOC, Santa Monica, California, April 1976.
- 3. Foster, R.W., "Alternative Fuels and Intercity Trucking," DOE Report HCP/M 3294-01, June 1978.

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SECTION 3

OBJECTIVES AND SCOPE OF ASSESSMENT

This section briefly states the objectives of the assessment and describes the technical scope of the effort.

A. OBJECTIVES OF THE ASSESSMENT

The primary objective of the effort reported here was to assess the status of the fuel cell/battery vehicle power system concept. This vehicle design approach is briefly covered from a technical standpoint in Section 1 and from an engineering history viewpoint by Kordesch, in Appendix A, as well as elsewhere in the report.

The specific objectives of the assessment are noted below:

1. Perform a literature search on fuel-cell powered automobiles, vans, trucks, and lift trucks. Define the technical problems, evaluate the near-term and market potentials, assuming there is a source of fuel. (See Section 4A, p. 4-1.)
2. Obtain the current views of DOE, GM, Ford, and MERADCOM on electric vehicles using a fuel-cell/battery combination (battery designed for 5 minutes of initial operation and for supplementary power during acceleration). Summarize work in progress by these organizations and their future interests in such vehicles. (See Section 4B, p. 4-12.)
3. Define the R&D focus required to make automotive fuel cells a viable transportation option, i.e., to effect a substantial market penetration. Determine which Government agencies, and organizations within, have funding responsibility. (See Section 4C, p. 4-22.)
4. Evaluate the relationship between battery-driven and fuel cell/battery driven vehicles, i.e., common technical problems and system components, as well as the respective advantages. Discuss how fuel-cell-driven vehicles might be affected in the market place due to the presence of battery-driven vehicles. (See Section 4D, p. 4-29.)
5. Obtain current views and outlooks of DOE and industrial organizations regarding the future availability of hydrogen and methanol derived from coal. (See Section 4E, p. 4-36.)
6. Prepare project report.

These objectives defined six tasks comprising the overall assessment. The findings resulting from these task activities are presented in Section 4.

One additional task was introduced during the course of the study: preliminary assessment of comparative vehicle simulation results. This added effort is in recognition of the value of having the results of computer-simulated driving-cycle performance for various fuel cell/battery vehicle power systems available for comparative analysis. The simulation work discussed in Section 4 derives from the computer-based analysis carried out by Drs. B. McCormick and D. Lynn of the Los Alamos Scientific Laboratory. (See Section 4F, p. 4-54.)

B. SCOPE OF THE ASSESSMENT

As sponsored by the Brookhaven National Laboratory (BNL), under Consulting Subcontracts 2690 and 2715, Escher:Foster Technology Associates, Inc. (E:F) carried out this assessment of the status of fuel cell/battery vehicle power systems during June through September 1979. This effort was supported under the Lawrence Livermore Laboratory cooperative study, "Energy Storage Systems for Automotive Propulsion", with funding provided by the Department of Energy, Division of Energy Storage Systems.

The assessment effort reported here was of a specific, focused nature rather than being exhaustive or comprehensive. As noted in the objectives, previously presented, responses to specific questions were desired. A general review of work-to-date in fuel cells for vehicle power systems, coupled with a summary of attitudes, views, and plans, if any, of involved groups in industry and Government comprised the basic target toward which the assessment team's efforts were directed.

Mr. Gerald Strickland of BNL managed the subcontract as Chairman of LLL's Chemical Energy Storage Panel. Messrs. William J. D. Escher and Richard W. Foster comprised the E:F assessment team. Mr. Raymond R. Tison assisted in fuels-oriented analysis reported in Section 4E. The E:F contribution required approximately 1-1/2 man-months of effort.

SECTION 4

TASK FINDINGS

A. LITERATURE SEARCH RESULTS

Objective of Task

The specific language of the Task 1 assignment was:

"Perform a literature search on fuel-cell powered automobiles, vans, trucks and lift trucks. Define the technical problems, evaluate the near-term and market potentials assuming there is a source of fuel."

Under Task 1, the study team carried out a limited literature search covering the use of fuel cells in surface-transportation vehicles. Particular emphasis was placed on citations relating directly to fuel cell/battery power systems for transportation applications. Based on the findings, an assessment of technical problems and the potential for future market penetration by such systems was prepared. This assessment was both task-related and, more generally, carried out to provide an overall basis for this effort. Therefore, in this respect, the findings are incorporated throughout the report as well as in this section.

Approach

Since an exhaustive search of the fuel cell literature was beyond the scope of the assignment, a "focusing means" was sought to permit the identification of immediately relevant citations. Such a means was found in an initial scanning of bibliographies (e.g., ASME, SAE), proceedings (e.g., Intersociety Energy Conversion Engineering Conference [IECEC]), and Journal of Technical Articles (e.g., Automotive Engineering, International Journal of Hydrogen Energy), and technical reports (e.g., from ERDA, DOE, and NASA).

The scope of the search has been limited to transportation aspects of the reported fuel cell work. Literature published by the Society of Automotive Engineers proved to be reasonably comprehensive in subject coverage. This was augmented by additional literature deriving from the assessment team's direct contacts with workers in the fuel cell/transportation field.

Presentation of Findings

Selected references are presented as a bibliography at the end of this section.

On the specific subject of demonstration vehicle systems employing fuel cell and fuel cell/battery power systems, Appendix A provides an excerpt of a recent paper by Kordesch, in which he briefly notes past hardware-oriented vehicle projects. As noted, this survey does not include the recent and ongoing fuel cell/battery powered fork-lift truck of MERADCOM or the golf-cart test unit of LASL.

For completeness in the state-of-the-art review sense, the reader is also advised to review the results of the assesment team's contacts with selected representatives of industry and Government (including several national laboratories) reported on in the next section (Section 4B).

The Transportation Fuel Cell vis-à-vis Battery Literature

Fuel cells, as applied to surface vehicle propulsion have a rather limited and uneven background, one extending roughly over the decades of the 1960's and 1970's. Efforts involving the combined fuel cell/battery power system represent a more limited subset of this field, being first demonstrated in operating systems in the late 1960's and early 1970's by Shell Research Ltd. and Union Carbide Corp. (See Appendix A.)

On the other hand, the much more extensive battery development activities for vehicle power systems applications have led to a very extensive technical literature base (not covered by this assessment). The U.S. work in batteries has been accelerated by support programs related to the focused thrust associated with the enactment of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (Public Law No. 94-413).

The summary point appears to be that improvements in available, and projected-to-be-available battery capabilities, resulting from funded and ongoing battery vehicle development and demonstration projects,

will support the battery subsystem of future fuel cell/battery vehicle power systems. However, some battery development to this end is indicated.

Background for Transportation Fuel Cell Systems

A broad-ranging review and prognosis covering fuel cell systems as transportation power systems is given by Schlatter in a 1967 paper (see bibliography section), in which he stresses the very major technical and economic impediments to be overcome (at that time).

He contrasts the \$3/kW internal combustion engine* with a "most optimistic" \$50/kW fuel cell, citing the lowest quoted estimate for production fuel cells of 100 kW and larger capacity by ASEA of Sweden as \$500/kW.** He sums up prospects with the statement:

"Even granting fuel cell breakthroughs, it is unlikely that fuel cell power will offer spectacular advantages over internal combustion engine power. Vehicle applications which do develop may be expected first in specialty lines, not to any extent in private automobiles."

Schlatter notes that "fuel cells may someday replace some batteries in electric vehicles" (thus suggesting the basic rationale of the fuel cell/battery power system as covered in Section 1).

In his prepared comments on Dr. Schlatter's 1967 survey paper, John C. Orth of the U.S. Army Engineering Research and Development Laboratories, offers the following:

"This paper shows that today's conventional concept of both fuel cell power plants and electric vehicles is inadequate for practical fuel cell

* For a 100 hp automobile engine, this denotes a unit mass-production cost of about \$400. Escalating this cost at 6%/year to 1979 roughly doubles this to \$800, or \$6/kW.

** Present prospects for fuel cell and battery costs are discussed later (p. 4-8).

powered vehicle propulsion. However, the state-of-the-art does change and there are today proposals being entertained for unconventional approaches to both fuel cell concepts and vehicle configurations."

Swinkels of GMRL provides a broad technical view in this 1968 paper, "Electrochemical Vehicle Powerplants:"

"It is probably useful at this point to destroy the mental picture one has of a battery as consisting of two dissimilar plates placed in an aqueous solution. This is the form most conventional batteries have taken but it is unlikely that this type of electric powerplant will drive anything but a low performance, limited range vehicle.

"Neither the substance producers* nor the energy producers (that is, fuel cells and primary batteries) are of interest here but rather a combination of the two with the primary function of storing energy. We will, therefore, define a battery as a black box into which we can put a given amount of electrical energy, store it in the form of chemical energy, and retrieve a smaller amount of electrical energy at a later time." (emphasis and footnote added).

Hybrid Battery Concept

An all-battery analogy of the fuel cell/battery power system is the so-called hybrid battery system, for which several references were examined. Laumeister of the General Electric Co. describes the operation of a lead-acid (energy battery)/nickel-cadmium (power battery) in GE's "Delta" (for Developmental Electric Town Auto) vehicle in an SAE paper of 1968.

In the following quotations from this reference, the term "drain rate" refers to discharge rate as related to power density (watts/pound), high

* Devices which accept electrical energy and materials and produce a new material(s), e.g., water electrolyzer, a secondary storage battery in its charging mode.

values of which are associated with the nickel-cadmium "booster battery." The "main battery" in the GE system, a lead-acid unit, is used for its high energy density, which would be provided by the fuel cell in the system concept being assessed in the present report.

"The hybrid battery concept, as applied in the GE experimental vehicle, is a solution to the limited drain rate problem for most vehicle applications. A cadmium battery capable of very high discharge rate is paralleled through electronic control circuitry to the main battery. This circuitry automatically senses the drain rate and brings on and gradually increases the current delivery from the nickel-cadmium booster as the load increased beyond the economical capability of the main battery. The control circuit also automatically recharges the booster unit when it is not delivering current. The recharge is cut back to a trickle level once the booster is recharged and cut off when the vehicle key is turned off.

"The hybrid or booster battery system cannot solve the drain rate problem for all batteries. The main battery must have a sufficient power delivery rate to propel the vehicle at continued steady cruise up to its maximum recommended speed. The booster unit, while providing power for occasional hill climbing peaks, will not be recharged during cruising unless the main battery's output exceeds the cruising rate power demand. This relationship must be closely studied when considering high energy density, low drain rate batteries, since the battery weight will be determined by the drain rate factor (not the desired range) and may require a unit as heavy as the present lead acid."

In a later SAE paper (1971), Brown of GE further describes this hybrid battery approach and, addressing control and interconnection requirements, states:

"The batteries cannot simply be placed in parallel; they require a resistive connection between them and a variable connection to the load that protects the main battery from excess drain rates in meeting local demands and in recharging the acceleration battery. The resulting performance offers the advantage of reduced main battery weight, extended range, and responsiveness to acceleration demands."

Dalin and Kober of the Yardney Battery Corporation, in a 1969 SAE paper, describe another hybrid battery system for vehicle propulsion. A nickel-zinc battery is employed as the energy battery and an air-zinc battery* as the power battery. Nickel-cadmium batteries are rejected for widespread vehicle application because of the limited availability and high cost of cadmium, and the low energy density of the unit.

The Yardney researchers state that their work is predicated on non-use of any noble metal catalysts, which is believed to be incompatible with significant commercialization. Also, possible problems in recharging the nickel-zinc (power battery) from the energy battery are noted: e.g. the power battery might degrade under fast-charging conditions, as would be likely under normal driving cycle operation.

Finally, this paper reflects how the overall hybrid battery energy density (Wh/lb) and power density (W/lb) characteristics can be tailored as a function of the mix of two battery types chosen. This mix is suggested to be a strong function of the vehicle type and, especially, the driving cycle involved.

Fuel Cell/Battery Power Systems

A non-vehicle fuel cell/battery power system consisting of a closely integrated molten carbonate fuel cell and a molten electrolyte battery is suggested by Frysinger in his 1969 SAE paper. He emphasizes the fast transient load response of this combination in stationary-application service.

A concise review of fuel cell and fuel cell/battery vehicle power system developments which reached the hardware stage is provided by

* Interestingly, "air scrubbing" to remove carbon dioxide is assumed for the air-zinc battery as was done by Kordesch for the hydrogen-air fuel cells used in his demonstration automobile. (See Appendix A.)

Kordesch in his 1977 paper. This paper, as reproduced in the proceedings of the LASL Workshop (McCormick et al., 1977), is excerpted as Appendix A of this report. The reader is referred to this in lieu of repeating this coverage here.

Breele of the Institut Francais du Petrole presented a planning paper before the SAE in 1974 on hydrogen fuel cells, demonstrating its practicability in a 4-passenger urban automobile. He notes a cost-competiveness with conventionally fueled thermal engine automobiles, and concludes:

"The only remaining problem with regard to fuel is thus that of safety when hydrogen is used in a vehicle. The only way to obtain data required for answering this important question is to experiment with hydrogen under various operating conditions."

In a 1978 review of recent overview papers of electric vehicle development and demonstration programs for the United States (Esposito, Dustin and Denington), the United Kingdom (Samuel), and the Federal Republic of Germany (Brader and Stephan), no fuel cell activity is cited.*

In his 1978 paper, Dowgiallo of MERADCOM summarizes the substantial work with a fuel cell/battery system powered fork-lift truck during the period from 1975-1978. This project is discussed in following Section 4B.

The current cooperative effort involving MERADCOM, LASL, and BNL was summarized at the 1979 IECEC (McCormick et al.). The earlier proceedings of the 1977 "Fuel Cell in Transportation Applications Workshop" held at LASL provides a comprehensive technical review of the status of the applicable technologies. This cooperative effort is a continuing activity.

Not yet reported is the recently completed LASL golf-cart engineering system using a hydrogen-fueled phosphoric acid fuel cell/battery power system. Operation of this unit was achieved in September 1979.

* However, a substantially funded and continuing effort by a joint Dutch/Belgium group (ELENCO) on transportation fuel cells is underway. See special note at the end of Section 4E.

Walsh, of the Argonne National Laboratory, has presented a recent (April 1979) review of the status of advanced batteries in the context of electric vehicle usage.

Current Estimates of Vehicle Fuel Cell Costs

Regarding current estimates of transportation fuel cell costs, in their 1979 IECEC paper, McCormick et al. cite \$200/kW for an automotive-sized (15 kW) methanol fuel cell/reformer system. This is a phosphoric acid electrolyte unit.

Recent estimates for solid polymer electrolyte (SPE) type fuel cell by General Electric Co., the principal developer of this technology, are less than this:

"The long demonstrated life of both the hydrogen/oxygen and hydrogen/air solid polymer electrolyte fuel cell combined with its compatibility with the CO₂ in both reactants makes the SPE fuel cell concept an attractive terrestrial power plant. Future cost projections as low as \$100/kW seem possible with the demonstration of performance at or above 1.0 A/cm² and the acceptance of a somewhat lower system efficiency. The selection of a slightly larger system rating (e.g., 25 kW) would also drive costs toward the \$100 kW."*

(Source: McElroy, 1978)

Recently published (1978-1979) information on vehicle alkaline fuel cell costs was not found in this assessment. A 1974 French reference (Breele) cites an 11.5-kW hydrogen-air fuel cell (presumed to be an alkaline) unit cost of \$560. The specific system cost is thus a low \$50/kW.

Current Estimates of Vehicle Battery Costs

Katz and Klunder of DOE provide estimates of costs for three near-term vehicle batteries for a range of assumed production levels for the period of from 1980-1984. This information is summarized below

* However, as discussed with McElroy in a visit to GE on 8 August 1979, a cost estimate of \$200/kW was offered.

for the 1984 case. (See also earlier Table 1-2):

	Batteries Per Year <u>Per Contractor</u>	<u>Battery Price, \$/kWhr</u>
Lead-Acid	2000	60
Nickel-Iron	500	300
Nickel-Zinc	500	250

Again, the all-battery electric vehicle is the intended use for the batteries covered in the above estimates. It has been noted (e.g., by MERADCOM) that batteries for fuel cell/battery systems may have some differing technical requirements which should be addressed at an early point. It is not possible to estimate the related impact on price, if any.

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B. CURRENT VIEWS AND WORK IN PROGRESS

Objective of Task

Under Task 2 of the assessment, the study team carried out liaison with Government and industry personnel in order to -

"Obtain the current views of DOE, GM, Ford, and MERADCOM on electric vehicles using a fuel-cell/battery combination (battery designed for 5 minutes of initial operation and for supplementary power during acceleration). Summarize work in progress by these organizations and their future interests in such vehicles."

Approach

The assessment team proceeded on this task effort through direct contact with the designated Government and industry organizations, namely, the U.S. Department of Energy (DOE), the U.S. Army Mobility Equipment Research and Development Command (MERADCOM), General Motors Corporation (GM), and the Ford Motor Company. This liaison was performed through facility visits, with the exception of MERADCOM, whose representatives were contacted by telephone and met with at locations other than Fort Belvoir, Virginia. A number of other contacts were also made. (See Table 4-1, p. 4-21.)

Summary of Findings

A summary of findings of current views and work in progress by the automotive industry and by the Government and national laboratories is presented below.

Automotive Industry Contacts

1. The automotive industry is not presently carrying on transportation fuel cell applications research and development which would be supportive of fuel cell/battery vehicle power systems.
2. However, the industry sustains an active interest in the potential of the fuel cell, associating it most directly with further advancements beyond battery power systems in electric vehicles.

3. Industry contacts generally reacted to the assessment team's contacts by inquiring if any advances in fuel cell costs, weights, volumes, and operating complexity had occurred to rekindle interest in fuel cells for vehicle use.
4. Of the methanol and hydrogen fueled alternatives considered in the present assessment, the possibility of methanol use in onboard reformer units was more readily accepted by industry contacts than hydrogen itself, although some interest has emerged in the latter at one company.
5. A specific concern was expressed about the potential supply limitations for the platinum group catalysts used in fuel cell electrodes if true automotive production volumes are ever to be achieved.

Government and the National Laboratories*

6. The thrust of current Government-supported fuel cell work is not directed to surface transportation applications but rather to 1) the electric utility, and 2) spacecraft and aircraft power system applications. (However, see Items 7, 9, and 10, below.)
7. The only pertinent fuel cell/battery vehicle system activity noted is that being cooperatively carried out by the U.S. Army MERADCOM, LASL, and BNL, with the former having operated an actual fork-lift truck using this system over realistic duty cycles in the laboratory during the period from 1975-1978.
8. Programmatically, the DOE electric vehicle activities being carried out under Public Law No. 94-413 (electric and hybrid research, development and demonstration act) exclude the fuel cell. It is not included in the extensive and continuing study effort on "Energy Storage Systems for Automobile Propulsion," being led by Lawrence Livermore Laboratory (LLL) (even though hydrogen systems for internal combustion engines are included).**
9. Existing and ongoing work in the field of fuel cell/battery power systems appears presently limited to -
 - A MERADCOM fork-lift truck outfitted with a metal-hydride hydrogen storage system by Billings Energy Corporation (partly supported by Brookhaven National Laboratory).

* Note: Generally, the efforts being carried out at the national laboratories are supported by the U.S. Department of Energy.

** However, subsequent to the preparation of the present report, fuel cell power systems for automobile propulsion were cited in the LLL report in the series (Draft UCRL-52841, Vol. 2, September 1979).

- Modified golf-cart test vehicle recently completed by Los Alamos Scientific Laboratory (LASL) operating on onboard pressurized gas cylinders of hydrogen (two steel breathing-air tanks).
 - Continuing vehicle/driving cycle computer simulation studies at LASL, including the technoeconomic characterization of several highway vehicle systems (city bus, highway bus, delivery van, and automobile).
10. A modest effort entitled "Development of Fuel Cell Technology for Vehicular Applications" is in its second year at BNL, in which alkaline (KOH), phosphoric acid, and solid polymer electrolyte fuel cell technology is being experimentally pursued at small scale.

Discussion of Automotive Industry Contacts

In discussions with representatives from the Ford Motor Company's Scientific Research laboratories and the General Motors Research Laboratories, we gained the impression that there is no work of any magnitude presently underway on the fuel cell/battery power system concept. Outside of some basic electrochemical research, little in the way of directed fuel cell R&D is being presently supported within these automotive companies.

However, there was evidenced a sustained interest in the potential of the fuel cell for transportation, as well as a history of nominal involvement in fuel cell research and development extending back to about the mid-1960's. Ford mentioned its support of a multi-sponsor activity in transportation fuel cell systems carried out in the mid-to-late 1960's by Battelle Columbus Laboratories. General Motor's "Electrovan" project, a hydrogen-oxygen alkaline electrolyte fuel cell powered experimental vehicle, dates back to the same time period. However, current or recently carried out work in transportation fuel cells, other than for the purpose of "maintaining awareness," was not evidenced at either Ford or GM.

The attitude taken by our bringing the subject of fuel cell/battery propulsion systems up before these automotive contacts was of the nature

of a question:

"What is there, new and different, about this concept which would make it worth pursuing?"

However, it also became clear that fuel cells were viewed as "further advanced" elements in the general context of electric vehicle systems for which the two companies have substantial activities in progress.

Although no concerted attempt was made to respond to this question, specific areas of automotive industry concern as to the implied drawback of fuel cells in an overall context of alternative vehicle propulsion systems were asked about. Both general and specific comments are summarized below:

- Although evidently committed to carrying out electric vehicle research, the basic thesis that this approach should be a preferred one for reducing automotive petroleum use appeared not generally accepted. One comment was that an equivalent effort to change-over electrical generating plants from oil to coal would be far more effective in pursuing this aim.

Technically, electric vehicles of any kind (fuel cell systems included) are much more massive systems than those in use today. With major efforts of the industry being focused on weight reduction programs and vehicle down-sizing, electric vehicles "buck the accepted trend." ("Vehicle energy use is almost directly a function of weight at the wheel in residential and metropolitan driving.") The obvious (but unanswered) question then, is: What weight-reduction leverage would introduction of the fuel cell provide to electric vehicles?

On a positive note, based upon one representative's 16 years of direct experience in electric vehicle activities, it was projected that the "frustrations" of the all-battery approach would likely engender renewed interest in the fuel cell. Not-so-positive was his follow-up point that only more frustrations, not success, with the fuel cell would result from such renewed interest.

More broadly, it was sensed that the automotive people increasingly perceive the main thrust for solving the problems attendant to transportation dependency on oil (especially imported oil) to be the development of alternative sources of conventional finished fuels usable in conventional cars, from domestic coal and oil shale.

With respect to the two fuel forms being addressed in this assessment -- methanol and hydrogen -- industry contacts indicated that methanol was a much more credible alternative. Although concern was expressed over the implied methanol production and delivery requirements of large-scale vehicle use, the equivalent needs for hydrogen were seen as a much tougher challenge.

Also, whereas onboard storage system and vehicle fueling requirements for methanol were perceived as reasonable extensions of the present liquid fuels state-of-the-art, those for hydrogen would be more difficult to meet. However, it was not clear that the industry people were necessarily aware of recent advances in metal hydride or cryogenic liquid onboard containment technology and fueling techniques.

One automotive company (Ford) had recently initiated a one-year comprehensive in-house survey and assessment of hydrogen as a future automotive energy form, but no conclusions are yet available.

A specific concern is that of the problem of supply for noble metal catalysts as required in (some)* fuel cells. It was noted that where about 2 to 4 grams of platinum catalyst per vehicle are used in catalytic converters, the order of 30 grams per vehicle have been estimated for a typical vehicle fuel cell installation. Apparently, cost is less of a concern than the feasibility and reliability of expanded supplies of platinum group metals from South Africa and the Soviet Union (which supply about 70% of current U.S. demand.¹)

* Alkaline fuel cells, specifically, do not require noble metal catalysts.

Technically, and within the electric vehicle context, the automotive contacts uniformly tended to regard the fuel cell as an "energy battery" which could match and complement the "power battery." Both Ford and GM noted the established "hybrid battery/battery" system concept as an analog to the proposed fuel cell/battery system.

Discussion of Government and National Laboratory Contacts

As an overview, current Government programs supporting fuel cells are only minimally directed to surface transportation applications. There are exceptions to this, such as the U.S. Army MERADCOM efforts on fork-lift trucks and similar applications and modest efforts at BNL and LASL to be discussed (supported by DOE). This cooperative work is reflected in a jointly authored technical presentation.²

The major Government-supported programs are the following:

1. DOE's electric utility fuel cells power plants program focusing on the 5-MW class and larger of phosphoric acid (first generation) and molten carbonate (second generation) system applications based on hydrocarbon fuels.
2. NASA's spacecraft power system programs which include alkaline and solid polymer electrolyte fuel cells development for the Space Shuttle and advanced space applications based upon hydrogen-oxygen reactants.
3. DOD's ground-based aircraft and spacecraft power system programs which parallel NASA's to some extent, but which include phosphoric acid electrolyte fuel cell developments under the Army (MERADCOM) for limited transportation applications (to be discussed in detail below).
4. Several of the national laboratories, carrying out DOE-sponsored activities, have expressed interest in fuel cells for transportation applications. In several cases, efforts are underway in applications studies and in research, development, and demonstration:
 - Through its Energy Storage and Conversion Division, BNL initiated a program entitled, "Development of Fuel Cell Technology for Vehicular Applications," in Fiscal Year 1978. The initial year's work, in collaboration with LASL and MERADCOM, included a survey of the fuel cell and battery state-of-the-art. Small-scale experiments with three types of fuel cells were carried out: phosphoric acid electrolyte, solid polymer electrolyte, and alkaline (KOH) electrolyte units.³

- BNL is also cooperatively supporting an experimental fork-lift truck demonstration to be assembled and evaluated at MERADCOM. The specific subsystem activity being funded by BNL is an onboard iron-titanium metal hydride hydrogen supply unit being prepared by Billings Energy Corporation.
- LASL has developed, and is exercising, a computer simulation capability for fuel cell/battery powered vehicles which encompasses specific hardware descriptions to the component level. Once "designed," these vehicles can be operated over stipulated driving cycles and the fuel cell and battery outputs monitored in detail at any point during the simulated driving cycles, e.g., wide-open throttle, SAE J227 standard residential and municipal driving cycles.
- LASL has also assembled an experimental fuel cell/battery vehicle system based upon a golf cart. This engineering test and evaluation unit uses an Energy Research Corporation (ERC) fuel cell and conventional golf cart batteries. Hydrogen fuel is carried as pressurized gas in a set of SCUBA tanks. Initial operation of this test vehicle was reported to have been accomplished in late September 1979.
- Related to its continuing multi-year assessment of "Energy Storage Systems for Automobile Propulsion,"⁴ the LLL is reported to be examining the fuel cell/battery power system using its computer analysis capabilities.⁵ However, it is significant to note that fuel cell systems have not been included in the published LLL study reports to date. (See footnote, p. 4-13.)
- Argonne National Laboratory (ANL), which carries "lead-laboratory" responsibility for vehicle electric storage battery systems, is active in transportation battery research and development for DOE. A recent review of progress in the overall DOE program in this field was provided by Katz and Klunder.⁶

To date, the only Government-sponsored effort noted to have resulted in the actual construction and test of an operating fuel cell/battery vehicle system is that of the U.S. Army's MERADCOM, as reported by Dowgiallo and his colleagues.^{7,8*}

Four 1-kW phosphoric acid electrolyte fuel cells were connected in parallel and operated using hydrogen gas from four standard pressurized gas cylinders aboard the vehicle. MERADCOM is developing a methanol steam reformer to replace the cylinders in the future.⁸ The fuel cell

* To which could now be added the above-mentioned fuel cell/battery golf-cart-based engineering test unit of LASL.

stacks were derived using Engelhard Industries 750-watt stacks, to which additional cells were added to uprate these to 1 kW. Each stack is rated at 42 volts.

The battery complement consisted of 6 standard automobile starting/lighting batteries (Sears "Diehardtm" units, rated at 96 amp-hours at the 20-hour discharge rate). These were connected in two parallel branches of 3 batteries in series.

Load profiles for equivalent lift-truck operations were acquired in a special measuring program conducted by MERADCOM using a conventional 4000-pound capacity all-battery powered vehicle. In laboratory tests, using the derived load profiles, the fuel cell/battery powered fork-lift truck operated well over a 3-year period. The fuel cells have experienced over 250 hours of operation and 54 thermal (on/off) cycles. MERADCOM believes that the fuel cell/battery approach would greatly extend the range and performance of present battery-powered vehicles, and that other vehicles could be fitted with these power systems.

References Cited in Section 4-B

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3. McBreen, J., et al., "Development of Fuel Cell Technology for Vehicular Applications," Brookhaven National Laboratory, Annual Report for Fiscal Year 1978, November 1978.
4. Behrin, E., et al., "Energy Storage Systems for Automobile Propulsion: 1978 Study, Lawrence Livermore Laboratory Report UCRL-52553 (2 volumes), December 15, 1978.
5. Personal communication from G. Strickland of BNL, September 1979.
6. Katz, M.J., and Klunder, K.W., "The Department of Energy Electric Vehicle Battery Program: An Overview," DOE presentation at the 14th Intersociety Energy Conversion Engineering Conference, Boston, August 5-10, 1979.

7. O'Sullivan, J.B., Dowgiallo, E.J., and Snellings, I.R., "Hybrid Power Source for Material Handling Equipment," MERADCOM presentation at the 10th Intersociety Energy Conversion Engineering Conference, Newark, Delaware, August 18-22, 1975.
8. Dowgiallo, E.J., "A Fuel Cell-Battery Power Source for Electric Vehicles," MERADCOM presentation at the Fifth International Electric Vehicle Symposium, Philadelphia, October 2-5, 1978.

SPECIAL NOTE REGARDING EFFORTS UNDERWAY IN THE JOINT DUTCH/BELGIUM EFFORT BY ELENCO (and by Siemens AG in West Germany)

"In Europe, work continues on alkaline fuel cells for terrestrial applications. At the Electrochemistry Laboratory of Siemens in Erlangen, West Germany, 3.5 and 7 kW alkaline hydrogen/oxygen fuel cells have been built and tested. A program is now underway to construct a 20 kW unit (14). These units are being considered for standby applications, for example, in hospitals. The 7 kW unit which was completed in May, 1978 consists of a fuel cell stack and electrolyte regeneration for product water removal. The cell stack consists of 70 cells and it delivers 142A (420 mA/cm^2) at 53.8 V. The electrocatalysts for the anode and cathode are Raney nickel and doped silver respectively. The system weight is 85 kg and the volume 60 l. The unit reaches 45% of rated power at 20°C and reaches the desired operating temperature of 80°C in eight minutes."

"In 1974, ELENCO, an organization consisting of three partners: the Study Center for Nuclear Energy (SCK/CEN), Mol, Belgium; Dutch State Mines, Geleen, Netherlands; and Bekaert, Brussels, Belgium was formed with the aim of developing alkaline fuel cells particularly for transportation (15). Work to date has involved the design, fabrication and testing of a 10 kW fuel cell. The 10 kW system consists of three 36 V module stacks in series. Each module stack consists of six 6 V modules. Each module consists of 18 cells in a series-parallel. The active electrode area in the cells is 300 cm^2 . The present design point is 80 mA/cm^2 at 0.67 V per cell. ELENCO has also carried out technoeconomic assessments. The main applications considered are for use of hydrogen byproduct gas from the chloralkali industry and as power sources for buses, fork lift trucks and special purpose vehicles."

"The ELENCO program is being funded at a \$5 million dollar level for the first three years which ends in December, 1978. The program has been renewed for a second three-year term at a \$7 million dollar level. In the second period stress will be on improvements in power densities by about 50% and continuation of the systems studies to explore further applications."

Source: McBreen, J, et al., "Development of Fuel Cell Technology for Vehicular Applications," Brookhaven National Laboratory, Report FCT-1, May 1979.

Table 4-1. PRINCIPAL CONTACTS MADE BY ASSESSMENT TEAM (Note: Individual Contact/Visit Memoranda for Each Contact Listed are Provided in Exhibit A of the Study Report)

<u>Organization/Location</u>	<u>Division/Laboratory</u>	<u>Individuals</u>	<u>Type/Date of Contract</u>
<u>(Industrial)</u>			<u>(1979)</u>
Ford Motor Company Dearborn, Michigan	Scientific Research Laboratories	H. Stadler, J. Kummer, L. Unnewehr, C. Kukkonen	Visit, 15 June
General Motors Corp. Warren, Michigan	GM Research Labora- tories	P. Agarwal, R. Stebar	Visit, 5 July
General Electric Co. Wilmington, Mass.	Aircraft Equipment Division	J. McElroy	Visit, 8 August
Energy Research Corp. Danbury, Connecticut		D. Patel	Visit, 9 August
Engelhard Industries Div. Iselin, New Jersey	Fuel Cell Venture Group	G. Smith	Telecon, 1 October
<u>(Government)</u>			
Department of Energy Washington, D.C.	Division of Energy Storage Systems (STOR)	A. Landgrebe	Visit, 26 June
U.S. Army Fort Belvoir, Virginia	Mobility Equipment Re- search & Development Command	J. Huff, E. Dowgiallo	Meeting, 26 June Telecon, 26 September
<u>(National Laboratories)</u>			
Brookhaven National Lab. Upton, New York	Energy and Environment	G. Strickland, F. Salzano	Visit, 28 August Telecons, Numerous (June-September)
Los Alamos Scientific Lab. Los Alamos, New Mexico		B. McCormick D. Lynn	Visit, 15 August Telecons, Numerous (July-September)
Argonne National Lab. Argonne, Illinois		W. Walsh	Visit, 13 July

C. RD&D NEEDS AND OPPORTUNITIES

Objective of the Task

In Task 3, the Assessment Team attempted to develop a basic RD&D approach which would be most appropriate for forwarding transportation fuel cell technology from its current state, specifically to advance fuel cell/battery power systems toward a potential market-entry point.

The task objective was -

"Define the R&D focus required to make automotive fuel cells a viable transportation option, i.e., to effect a substantial market penetration. Determine which government agencies, and organizations within, have funding responsibility."

Approach

This task effort proceeded along two paths: 1) an evaluation of transportation fuel cell and battery technological and programmatic status, as derived from the preceding two task activities reported above, and 2) to develop a framework in which to view the fuel cell/battery power system concept as it might progress through the research, development, and demonstration phases and address the market-penetration opportunity, when and if this stage is reached.

These two areas are briefly discussed below. However, the specific observations, conclusion, and recommendations deriving, in part, from this task have been documented earlier in Section 2.

Technical and Program Status

As pointed out in the discussion of the technical literature and current contacts (Sections 4A and B), emphasis to date in fuel cell work has been other than transportation power systems oriented. Therefore, fuel cell powered vehicle efforts are limited, and more so, fuel cell/battery vehicle projects.

On the other hand, all-battery electric vehicle research, development, and demonstration work has been pursued actively over the years. Work has been considerably augmented in the United States in the past few years as a consequence of the previously mentioned Public Law No. 94-413 legislation stimulating an aggressive RD&D program.

In terms of the conventional progression of a technology from the research stage to the commercialization stage, Figure 4-1 attempts to roughly portray the status of the transportation battery, fuel cell, and fuel cell/battery technologies.

Heywood and Linden have provided a specific model of the 20-30 year life-cycle of automotive systems which is diagrammed in Figure 4-2.¹ This presentation can be taken to be generally applicable to all transportation systems which might employ fuel cell/battery power systems.

In relating Figures 4-1 and 4-2, it can be noted that the demonstration phases of the former are merged into the development and introduction stages of the latter. Respectively, commercialization is implicit in the introduction, mass production, and fleet turnover stages.

In review, fuel cell/battery power systems work is presently at the applied research stage and, therefore, the full RD&D cycle must be undertaken to achieve a market-entry or onset-of-commercialization stage.

RD&D Needs and Opportunities

Figure 4-3 provides a graphical basis for considering the general direction which research, development, and demonstration efforts for fuel cell/battery powered transportation systems might proceed in relationship to other programs.

Along the top horizontal line-of-progression is shown the in-being all-battery vehicle RD&D efforts stimulated and focused under DOE's implementation of Public Law No. 94-413 (hybrid activity not shown). To the extent which high power output battery and other component technology is being advanced, and products are being developed, this effort is directly supportive of the fuel cell/battery power system concept.

	BATTERY VEHICLE	FUEL CELL VEHICLE	FUEL CELL/BATTERY VEHICLE
RESEARCH			
DEVELOPMENT			
TECHNOLOGY DEMONSTRATION			
COMMERCIALIZATION DEMONSTRATION			
COMMERCIALIZATION			

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Figure 4-1. Status of the Transportation Battery, Fuel Cell, and Fuel Cell/Batteries Technologies

Figure 4-2. A Simplified Model of the Stages and Decisions in the Process of Automotive Technology Development and Production

Figure 4-3. Suggested Interrelationships Between the Three Design Concepts Assuming the Fuel Cell/Battery Designs Were to be Further Pursued.

Along the lower "fuel cell" line-of-progression, other than transportation applications are being presently addressed. Nevertheless, some substantial share of the associated technology advances are applicable to transportation fuel cells. In other words, potential technical and cost benefits are being accrued.

Thus, both the battery (upper) and fuel cell (lower) RD&D activities indirectly are supportive of a projected fuel cell/battery vehicle development and demonstration effort (middle line of progression). Such an effort does not exist at this time.

Although distinct development and demonstration stages will be required and are shown in the figure for the fuel cell/battery system, no special or dedicated research phase is indicated. This is because, if effective feedback can be maintained from the development effort, the existing battery and fuel cell research activities, and the supporting infrastructure, should be reasonably capable of supporting and completing the concept's research needs as these become apparent.

Going forward in time from the development stage, an ultimate market-entry and initial commercialization step is suggested for the fuel cell/battery vehicle system effort, provided the demonstration-stage results are sufficiently positive. As noted in Section 2C (Recommendations), this stage must be resolutely directed to the minimization and elimination of uncertainties of several types, such that commercial decision-making processes can operate effectively and that a sustained market penetration can be accomplished.

Regarding special opportunities which can be potentially addressed by the fuel cell/battery program element activity, were this to develop, perhaps the most impacting of these from today's vantage point is that of expanding the applicability of electric vehicle systems to new uses, previously viewed as beyond the "technological reach" of electric systems, and specifically all-battery systems.

However, a specific discussion of these possibilities is relegated to later Appendix C. The reader is referred to this discussion.

D. RELATIONSHIPS: BATTERY (ONLY) AND FUEL CELL/BATTERY VEHICLE
POWER SYSTEMS

Objective of Task

Task 4 of the assessment considers the fuel cell/battery approach in context with electric vehicle system research, development, demonstration, and commercialization activity:

"Evaluate the relationship between battery-driven and fuel-cell/battery driven vehicles, i.e., common technical problems and system components, as well as the respective advantages. Discuss how fuel-cell-driven vehicles might be affected in the market place due to the presence of battery-driven vehicles."

Approach

The information gathered in the literature search and those direct contacts already discussed, plus applicable in-hand background, were drawn upon in the discussion to follow.

General Relationships

On a technical basis, the fuel cell/battery power system vehicle concept fits in as a subset under the general category of "electric vehicles." In context with all-battery power systems, as currently stressed in the U.S.'s Electric and Hybrid Vehicle Research, Development, and Demonstration Act, program commonality of systems, subsystems, and components is expected to be much more the rule than the exception. Thus, there is a very strong "family relationship" apparent between the all-battery and the fuel cell/battery vehicle power systems approaches.

Further, several contacts in the fuel cell industry advised the assessment team to maintain comparisons of fuel cell vehicles with other electric vehicles. Comparisons to conventional internal combustion engine powered systems should be used with considerable caution.

This relationship can be illustrated with hybrid battery/battery (all-battery) power system discussed in Section 4A (GE and Yardney). The fuel cell as an "energy battery," limited in capacity only by fuel system capacity, would fit into the battery/battery system approach with no disruption or compromise to the hybrid concept previously discussed.

Rather, and this is seen as the basic "theme" of fuel cell/battery system proponentcy, integration of the fuel cell "energy battery" markedly improves the capability of the electric vehicle, e.g., provides needed range and endurance extension vis-a-vis all-battery systems.

Vehicle components under development for all-battery systems - controllers, instrumentation, motors, wiring and connectors, special ancillaries, and auxiliaries - will continue to be applicable to fuel cell/battery power systems. Thus, the integration of fuel cell subsystems into present (but suitably modified) electric vehicles seemingly could proceed without major new component development programs.

It would appear practical and desirable to use existing and service-proved electric vehicles for basic reliability purposes. NASA has observed in their recent state-of-the-art road-test assessment of all-battery vehicles:¹

"The reliability of the electric vehicles tested was poor compared to conventional vehicles. As there are presently electric vehicles in service that have demonstrated very high reliability, it is expected that as the industry matures the reliability of all electric vehicles will improve."

It can be thus inferred that any new-from-the-wheels-up vehicle specially developed for fuel cell/battery power systems evaluation would also tend to suffer from unreliability initially.

However, a number of differences are obvious as one addressed the fuel cell/battery approach in the context of all-battery vehicle systems. Key among these are -

- a. Fuel cell/battery vehicles require supplies of chemical fuels (methanol and hydrogen are emphasized in this study), and would not be directly charged from the utility electric grid.
- b. Battery technical requirements as applied to a "power battery" to be integrated with a fuel cell subsystem are likely to be different than heretofore applied (except as already examined in the hybrid battery/battery approach).
- c. In at least some fuel cell subsystems, reject heat will be available for uses such as vehicle passenger compartment heating (a problem area in all-battery systems).
- d. Vehicle unrefueled range and endurance capabilities, as indicated by preliminary driving cycle simulation runs (see Section 4F) can be equivalent to, and even superior to, conventional gasoline and diesel fuel vehicles, which is not the case with all-battery vehicles to date. (It is not yet clear that on-the-road performance: acceleration, hill-climbing, etc., can approach that of conventional vehicles, however.)

The above discussion suggests incentives for an examination of the fuel cell/battery approach. This would seem fully appropriate within the context of the ongoing electric and hybrid vehicles RD&D effort.

One major ramification external to the vehicle system is clear: A shift is indicated in basic energy supply, to be further discussed.

The Issue of Energy Supply

Fuel cells require a chemical fuel by nature. In the fuel cell/battery concept, the battery is recharged by the fuel cell; an electrical energy supply is not required. Such supply is required by the all-battery vehicle. Thus, electric utilities are found to be basic participants in the present electric vehicle program.

Fuel cell/battery vehicles might still be supplied energy from the electric utilities, however.* Based upon a conversion of electricity to hydrogen via water electrolysis, at or near the vehicle fueling point,

* The obvious alternative is supplying fuels in a mode analogous to the case of conventional vehicles. With methanol and hydrogen being "alternative fuels," activities under the existing DOE Alternative Fuels Utilization Program² are pertinent.

fuel cell/battery vehicles could be thus serviced by means of "hydrogen-via-electricity." Such a concept has been published,³ and discussions with selected utilities carried out.⁴ Generally, the scheme appears practical. The key issue, as yet not addressed, is the resulting cost of hydrogen "at the pump."

It may also be practical to provide methanol from electrolytic hydrogen. This would require a source of feedstock CO or CO₂, and an appropriate methanol synthesis facility. With electrolytic oxygen available as an off-setting byproduct, possibilities occur for synergistically integrating the methanol production facility with another industrial process requiring oxygen and giving off carbon dioxide.

Such a "methanol by wire" approach is quite analagous to the "ammonia by wire" concept which has been under consideration over the years. Obviously, the basic approach is not restricted to fuel cell/battery vehicle fuel supply applications.

An interesting alternative to electric utility supplied hydrogen-via-electricity, one that focuses on the sun as a renewable energy, is solar/hydrogen. A current study of this approach has indicated that several specific systems might be commercializable within the 1980-2000 time period:⁵ Technologies involved are thermal heat engines, photovoltaics, wind energy, and small hydropower.

A recent general review of hydrogen production and delivery means, oriented to automotive usage, has been published by the Aerospace Corporation.⁶ This and the general literature now available on hydrogen energy systems can be consulted for background.

Finally, as required in the present assessment task statement, the current views and outlooks of DOE and several industrial organizations on coal-based hydrogen and methanol are summarized in Section 4E.

Possible Market Place Interactions

The subject of market place interactions between all-battery electric vehicles, which are assumed to have substantial penetration, and fuel cell/battery vehicles, as these are to be introduced, is highly speculative at this point in time. In the first place, it is far from clear what facets of the transportation sector will in fact have battery-vehicle service in the decades ahead.

As evidenced in the enactment of Public Law No. 94-413, and its administration to date, it is clear that Government-stipulated actions may have a strong influence on battery-vehicle initial penetrations. Clean-air incentives, for example, could press electric vehicles into city-center service more aggressively than would otherwise happen strictly through "market pull" incentives.

If it is assumed that a substantial battery-electric market penetration has occurred, what then would be some of the considerations as fuel cell/battery systems reached market-introduction status? Here are some of the issues:

1. Electrical charging stations established for the battery-electrics would not be directly usable by fuel cell/battery vehicles (as discussed earlier).
2. Provided component commonality were to be widely achieved, the fuel cell/battery vehicles would provide a broader market to further support all-battery systems parts and service systems. This expansion of needs could provide the manufacturing and service industries with "new business" incentives.
3. Electric vehicle operators would be able to extend their operations, in certain cases, through the augmented capabilities of fuel cell/battery systems, and would expand their fleets and/or achieve an optimal mix of all-battery and fuel cell/battery vehicles.
4. With reference to the above point, it is not possible to state whether a balanced fleet mix would, in fact, be achieved in the long run. Alternatively, the fuel cell/battery systems might totally displace the all-battery systems except where the latter retain unique advantages, e.g., the requirement of operating directly from the electrical grid.
5. As for the battery manufacturing and service industry which is a key component of all-battery systems, the degree of dependence

on this industry for fuel cell/battery systems will be considerably less. Batteries comprise both a much lesser fraction of the vehicle overall power system complement in the fuel cell/battery case and should pose somewhat of a lesser technical challenge as well.

6. In comparison with the battery manufacturing and servicing industries, there is today no equivalent fuel cell industry. Within the industrial fuel cell organizations which are today involved in research and development activities, the great proportion of work going on is directed to other than transportation power system applications. If fuel cells are to ever enter the market place, an appropriate industrial base must be developed ahead of time.

Clearly, more attention must be given to the issue of all-battery vs. fuel cell/battery interactions in the market place. However, until clear trends emerge with regard to 1) the technical and commercialization success of fuel cell/battery systems, on the one hand, and 2) the anticipated market penetration of all-battery systems, on the other, assessments of this issue will remain speculative.

A step which might be fruitful, in examining such interactions, would be directed to the research, development, and demonstration operation of fuel cell/battery vehicles in direct comparison to all battery vehicles emerging from Public Law No. 94-413 supported programs.

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E. OUTLOOK FOR FUTURE AVAILABILITY OF HYDROGEN AND METHANOL FROM COAL

Objective of Task

Under Task 5 of the assessment, the general issue of future fuel supply for both hydrogen- and methanol-using fuel cell/battery powered vehicles was addressed. Focus was on coal as the primary energy resource for the production of these fuels. The specific task statement was:

"Obtain current views and outlook of DOE and industrial organizations regarding the future availability of hydrogen and methanol derived from coal."

Approach

Direct telephonic contacts were made with representatives in DOE and also in industrial and fuels research organizations involved in coal-based hydrogen and methanol production processes. In these contacts, emphasis was placed on soliciting candid views and outlooks for establishing an adequate supply of coal-based fuels, eventually capable of fueling substantial fleets of fuel cell/battery vehicles, assuming the latter's success in the market place.

Those organizations contacted included —

- DOE's Office of Fossil Energy
- DOE's Office of Transportation Programs
- Tennessee Valley Authority
- Institute of Gas Technology
- Exxon Research and Engineering Company
- Chem Systems, Inc.

No comprehensive review of the literature was pursued. However, some pertinent references were consulted as listed at the end of the section.

General Findings: Methanol and Hydrogen Industrial Practice
and Prospects for Coal Use

The prospects for coal-derived hydrogen and methanol being available in the market place for transportation fuel applications depends upon both the market demand and the coal supply. At the present time, coal availability is good due to excess mining capacity, but the hydrogen and methanol markets are too small to support coal conversion plants. In the not-to-distant future, this condition may be reversed as the synthetic fuel industry develops (i.e., synthetic crude, SNG, methanol, and hydrogen from coal) and competes with the electric utilities for the available coal.

Almost all of the methanol and industrial hydrogen produced in the United States today is manufactured via catalytic steam reforming of natural gas and, to a lesser extent, other light hydrocarbons.¹ Plant sizes for hydrogen production as represented by those located at U.S. refineries average about 50×10^6 Btu (16.3×10^9 Btu/day) of product gas per day. The largest plants are nominally 100×10^6 SCF/day (32.5×10^9 Btu/day).² Methanol plants are similarly sized, with the largest current plant producing up to 2000 short tons/day (39×10^9 Btu/day).³

Plants for producing hydrogen and methanol from coal are now being considered at the 1000×10^6 SCF/day and 2000 short tons/day size. However, prior to about 1977, most published data referred to planned plants having output capacities of about 250×10^9 SCF/day. It is these large multi-train plants that take advantage of substantially larger plant scale which promises the most attractive synfuel costs. However, these large plants are clearly too big for the current hydrogen and methanol requirements. At the 1975 hydrogen requirement (excluding methanol requirements) level of about 0.52 quad/year⁴ (Table 4-2), only about six large coal-to-hydrogen plants would be required, and for the 1976 methanol demand level of 3.1×10^6 tons,⁵ only one large coal-to-methanol plant would be needed. (By "large" is meant 250×10^9 Btu/day.) Thus, the total

current hydrogen and methanol market could be served with about 7 coal conversion plants, provided a system for product distribution existed.

Table 4-2.. 1975 U.S. HYDROGEN REQUIREMENTS²

	<u>quad/year H₂</u>
Refining Hydrogen	0.15
Ammonia	0.35
Methanol	0.06
Small User Hydrogen	<u>0.02</u>
Total	0.58

* One quad/year equals 10^{15} Btu/year. Overall U.S. energy consumption in 1978 was about 78 quads/year. (Source IGT GaScope, Spring 1978).

Since the market for large coal conversion plants has not yet developed, with the synfuel industry still "on the drawing boards," the smaller plants (a size previously considered as "demonstration") are now being considered for use in the existing market. Based on the results of economic studies recently reported,^{6,7} the prospects of "small" coal conversion plants being built looks promising. Figures 4-4 and 4-5 show the results of one such economic study.⁶ A 100×10^6 SCF/day plant would be equivalent to 32.5×10^9 Btu/day (higher heating value [HHV] basis), or about one-tenth the "large" plant mentioned earlier. As can be seen, methanol from coal appears to be attractive when compared with either natural gas steam reforming or partial oxidation of residual fuel oil. Hydrogen from coal, on the other hand, appears somewhat less competitive with existing supply technologies for the near term.

A special "Hydrogen From Coal Cost Estimation Seminar" was carried out under the sponsorship of the DOE and administered by the Billings

A-1979-12-057

Figure 4-4. Hydrogen Manufacturing Costs - Midcontinent Location⁶
 (\$/10⁶ Btu for 100 x 10⁶ SCF/day Plants, 1980 \$)

HIGHER HEATING VALUE BASIS: 10,259 BTU/LB.

A-1978-12-056

Figure 4-5. METHANOL MANUFACTURING COSTS - MIDCONTINENT LOCATION⁶
 (\$/Short Ton, 2000 Tons/Day Plants, 1980 \$) (Note: Estimated
 \$/10⁶ Btu Costs are Provided in Parentheses at 20.6 x 10⁶ Btu/Short
 Ton [Higher Heating Value])

Energy Corporation in June 1979. The assessment team was unable to acquire any documented results from this seminar in time to include in the current report. Based on several unofficial contacts, it is understood that hydrogen production costs of the order of \$4/million Btu were projected by the participants. If so, this is a substantially lower estimate than those developed by Exxon Research and Engineering Co. (Figure 4-4) and by the Institute of Gas Technology. (See Bibliography Section 4A.)

The comparison of coal conversion product costs with products produced via conventional means, however, may not be the deciding factor in selecting future hydrogen and methanol production facilities. Other factors such as reformer feedstock supply, recognition that coal conversion is a "next generation" production method, coupled with the need for operating experience and the potential to expand a facility to meet increased markets, may foster a switch to coal conversion plants somewhat before comparative product cost would otherwise dictate. In addition, Government support of initial projects can increase the attractiveness of earlier starts.

An example of this early switching to coal conversion is reflected in a current W.R. Grace Company project, which will provide a small coal gasification plant as part of an ammonia production facility. The coal conversion plant is currently in the preliminary design stage, supported by the DOE and is competing for continued DOE support with another coal conversion plant being designed for the production of industrial fuel gas. The latter project is being conducted by the Memphis Power and Light Company.

Another example is a 10×10^6 SCF/day coal gasification plant being built to supply hydrogen in an ammonia plant at the Tennessee Valley Authority (TVA), National Fertilizer Development Center in Muscle Shoals, Alabama. This plant is expected to be operational by mid-1980.⁹

While it appears that coal conversion plants will be eventually built within the hydrogen and methanol industries, major activities are not anticipated until after 1990.¹⁰ However, once these plants are built, it is possible that some excess capacity (that which is planned to support near-term growth) will be available to support some transportation alternative fuel requirements. If this market then appears attractive to industry, the existing small plants could be enlarged and new plants constructed.

Incentives and Special Supply Possibilities

Another possible incentive for early application of coal fuels production facilities, and the subsequent potential of some portion of the installed capacity being available to support fuel cell/battery vehicles, is transportation use of gasoline-methanol blends. The advantage here is that methanol from domestic coal would displace expensive imported crude. However, certain components within present automotive fuel systems are not compatible with methanol.¹¹ Examples of such incompatibilities include: common elastomeric seals and lines, certain plastic items, the tern-metal plating in fuel tanks, and possibly die-casting alloys used in fuel pump and carburetor components (long-term effects). Appropriate changes are indicated.

At least one other methanol-from-coal source warrants mention. In 1977, a study conducted for ERDA, Division of Transportation Energy Conservation, identified a potential methanol-from-coal source to support vehicle fleet tests.¹² This source consisted of large coal gasification plants being planned in support of the natural gas industry. With the addition of a methanol synthesis unit, these plants would co-produce methanol and SNG. Driving this potential to produce methanol as a co-product is the requirement by several plants, those using the Rectisoltm gas clean-up system, for methanol as a required clean-up system feed material.

The study further identified that a two unit, 250×10^6 Btu/day plant, planned by American Natural Gas and Peoples Gas Companies, would

employ a methanol synthesis unit. Since this unit would be part of the first unit built and construction plans called for only one unit to be built initially, excess methanol production capacity would exist and could be used to support an alcohol fueled vehicle test fleet. This capacity however, would not be available upon completion of the second gasification unit. However, financing problems currently have all major U.S. SNG coal programs halted.

The Coal Supply Issue

There is little doubt that U.S. coal reserves are adequate to support the U.S. energy needs for many years. The Institute of Gas Technology recently estimated a coal-use life span of 104 years, based on a 4% coal-use growth rate and a recoverable reserve of 1036×10^9 tons.¹³ With slower growth rates, and/or more optimistic estimates of recoverable reserves, even longer coal based energy life times can be projected.

The concern in supplying the coal for projected new coal conversion plants is not the ultimate life span of the U.S. coal supply but the rate at which the coal industry can expand. As stated earlier, the industry has some unused capacity at the present time.¹⁴ In the next few years, this capacity will most likely be used up by both new and non-coal fired plants switching to coal. Once this capacity is in full use, the availability of coal for the synfuels industry, of which hydrogen and methanol may only be a minor part, and the electric power industry will depend on the attainable growth rate of the coal industry.

This growth rate, viewed realistically, is expected to be slow, probably about 2% per year, not the 7% which would be required to double coal production as called for in Project Independence.¹⁵

Figure 4-6 presents a graphical representation of the key factors and their interaction, which control the development of coal supply.¹⁶ In this model, four delaying factors are indicated and these limit the

Figure 4-6. Coal Development System.

coal industry growth once an expected demand occurs. Examples of these delay factors are:

- New Underground Mines: 7-10 years to reach full production^{14,15}
- Mining Equipment:
 - Surface: Drag lines take 5 years for delivery after date of purchase plus 6-18 months for on-site erection.¹⁵
 - Underground: About 1 year for delivery after date of purchase.¹⁵
 - Coal Cleaning Plants: 3-3.5 years for construction.¹⁵
- Labor: It takes 2-3 years to train underground miners plus there is real concern about the availability of potential miners to train and mining engineers.^{14,15}
- Transportation:
 - Rail: The rail industry will require major additions to their rolling stock. The current car building and locomotive industry is basically sized to meet replacement schedules. Thus, this industry must also expand.¹⁷
 - Slurry Pipeline: Competes with rail in some cases, but requires railroad company rights-of-way approvals for implementation. It also requires large capital investment and water supplies, either being potentially limiting factors.

With the coal industry expected to grow at a slow but steady rate, the future availability of hydrogen and methanol from coal may well depend upon the strength of the market and the price which the hydrogen/methanol industry can afford to pay for coal in the competitive market place.

Fuel Requirements of Fuel Cell/Battery Vehicles

First, it should be recognized that initial fleet demonstrations of fuel cell/battery automobiles, in analogy to the present electric vehicle situation, will have almost no effect on the hydrogen or methanol production industry. However, once the penetration reaches the 1% to 2% level (i.e., 1 to 2 million vehicles), the impact would be pronounced when measured in terms of the existing hydrogen and methanol market. But in terms of coal requirements, such a penetration would be very small compared with the current coal production level. Table 4-3 illustrates this point.

Table 4-3. COMPARISON OF FUEL CELL/BATTERY FUEL REQUIREMENT WITH CURRENT
U.S. METHANOL, HYDROGEN, AND COAL PRODUCTION

Fuel Requirement ^a for a 2% Penetration	1977 Estimated ^c Meth- anol Demand 10 ¹² Btu/year	Total 1975 Hy- drogen Demand ^b	Coal Requirements ^c for a 2% Penetration		1976 U.S. Coal Production 10 ⁶ ton/yr
			Hydrogen	Methanol	
			10 ⁶ Tons/yr		
87.7	65.8	580	6.1	9.1	671

^a Assumed fuel efficiency = 3720 Btu/mile. Average vehicle miles = 11,800 miles/year.
2% penetration = 2 x 10⁶ vehicles.¹⁸

^b See Table 4-2.

^c Coal to hydrogen efficiency = 60%. Coal to methanol efficiency = 40% (nominal assumptions).

A Special Note: Methanol Vs. Fuel-Grade Methanol

One issue bears special consideration regarding methanol from coal: its purity. As discussed by the Institute of Gas Technology, anticipated "fuel-grade methanol," which may be fully acceptable to combustion-based power systems vis-a-vis pure methanol (e.g., chemical or reagent grade), could pose problems in an onboard vehicle reformer type methanol fuel cell system:¹⁹

"The economics of methanol manufacture for fuel purposes may impose a fuel composition containing small amounts of high-molecular-weight alcohols. 'Methyl fuel'* is such a product. In direct combustion, these higher alcohols should not pose a problem because they would be burned along with the methanol; however, the presence of these higher alcohols in a reformer fuel stream could lead to catalyst poisoning and deactivation. If the reactor temperature is below the reforming temperature of the alcohol, higher alcohols may pass through unreformed. Possibly, catalyst deactivation would occur by carbon deposition, polymerization, or other processes resulting from partial reformation. We know that temperatures higher than the methanol-reforming temperature of 505°K (450°F) are required to reform the higher alcohols. For example, the reformation temperature for ethanol is reported by Green²⁰ as 672°K (750°F), and higher alcohols reform at even higher temperatures, which can approach the reforming temperature of gasoline at 1060°K (1440°F)."

In its experimental evaluation of a representative methanol steam reforming catalyst unit, IGT indeed ran into difficulties with synthesized fuel-grade methanol after achieving 98% conversion efficiency of laboratory-grade methanol over a 280-hour run. Their results and conclusions are stated below:

* Methyl fuel is a registered trademark of Vulcan-Cincinnati, Inc. It is a methanol-based fuel with controlled percentages of higher alcohols and essentially zero sulfur, nitrogen, and metals content. Other details are given in Reference 19. (IGT's Reference 19 is listed as Reference 20 in the present report.)

"At the end of the laboratory-grade methanol run and after obtaining the space velocity and temperature effects data...we checked the condition of the catalyst by operating the reactor at the same conditions with a 1:1 molar laboratory-grade methanol-water mixture as fuel. Conversions of 98.4% of the methanol fed (for 30 hours) indicated that the catalyst was in good condition, so we changed the feed to fuel-grade methanol (98% methanol, 1.7% water, and 0.25% isobutanol, and 0.5% ethanol, by weight) and water (1:1 molar ratio). The conditions were the same as before, temperature ranging from 505° to 510°K (450° to 460°F) and a theoretical space velocity of 440 hr⁻¹. Immediately after the start of the run, we observed a drop in the amount of alcohol reformed, from the 98+% of the laboratory-grade methanol run to 93%. Furthermore, after 40 hours of operation, we observed a substantial drop in the amount of alcohol reformed, from 93% after 40 hours to 70% at 140 hours. After 140 hours and to the end of the run at 530 hours, a certain stability was reached; the 'rate of deactivation' held to an average decreasing rate of 0.025% of methanol reformed per hour. The drop in 1/4 reforming efficiency between 40 and 140 hours is attributed to carbon deposition* and deactivation, which might be the result of a loss of reaction sites and surface area. From 140 to 530 hours, the entire loss of reforming efficiency could probably be attributed to catalyst deactivation.

"During this run, checks on the composition of the liquid collected showed traces of aldehydes, ethanol, and isobutanol. This indicates that dehydrogenation of alcohols occurred to a small extent and also that most of the higher alcohols were being reformed. Therefore, we concluded that the higher alcohols present in fuel-grade methanol resulted in a significant deactivation of activity over the 500-hour test run. We conclude that investigations are needed to clarify the mechanism of deactivation and to improve the catalyst's resistance to fuel-grade-methanol poisoning."

Figure 4-7 (Figure is from the IGT Reference 19) presents the data in a plot of percent methanol reacted vs. time. It shows both the lab-

* The catalyst at the end of the endurance test contained 4.4% carbon, by weight.

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Figure 4-7. IGT Laboratory- and Fuel-Grade Methanol Steam Reforming Results

oratory-grade methanol (left-hand portion of the plot) and the synthesized fuel-grade methanol (right-hand portion) performance.

Researchers at the Brookhaven National Laboratory have suggested two technical approaches for handling this potential problem with fuel-grade methanol.²¹ The first is to avoid the problem by changing from the 1:1 molar ratio tested by IGT (see preceding quotation, p. 4-48) to a 1:1 volume ratio. This has been shown experimentally to work well without producing catalysis deactivating carbon deposits.

The second approach BNL has suggested is applicable to catalyst bed reactivation, once such carbon deposits are formed. This can be done by simply heating the affected catalyst bed to the order of 600°F. A third approach deals with the alcohol formulation itself and is described next.

The assessment team obtained expert opinion from a methanol-from-coal facility engineering firm regarding the technical and cost implications of specifying an upgraded (non-fuel) grade of methanol to avert this potential problem. A representative of Chem Systems, Inc., who contributed to the earlier BNL-supported study of methanol (and other chemicals)⁶ indicated the following:

If initially designed for chemical-grade methanol, a coal-methanol plant would produce product at only slightly higher cost (i.e., 5% to 10%) than otherwise with fuel-grade product.²² Thus, it appears that the catalyst compatibility problem described in this special note can be obviated at little cost, provided effective planning is carried out regarding supply.

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F. PRELIMINARY COMPARATIVE VEHICLE SIMULATION FINDINGS AND
RELATED DISCUSSION

Background

As stated in Section 3, an additional unscheduled task was added to the assessment effort, based on the recognition of the substantial value of simulations of representative fuel cell/battery powered vehicle systems operating over several driving cycles.

This simulation work was carried out at LASL by Drs. B. McCormick and D. Lynn, and their contribution is acknowledged by the Assessment Team.

Objective of Task

It was desired to have documented representative, if preliminary, fuel cell/battery vehicle run data for both methanol- and hydrogen-fueled systems. Such parameters of interest as endurance and range, over several driving cycles, and ultimately some idea of fuel operating costs, were desired.

Approach

The LASL investigators utilized their existing computer program, which is capable of accepting real-hardware component characteristics operating over realistic operating ranges (not as lumped efficiencies) to simulate a fuel cell/battery power system. External factors such as aerodynamic drag, rolling friction, etc., are also realistically represented in the program.

Three driving cycles were operated within the limited investigation undertaken in support of the assessment:

1. Wide-open throttle-acceleration from standing start to a maximum sustained speed
2. SAE J227R Residential Cycle
3. SAE J227M Metropolitan Cycle.

Vehicle and Fuel Systems Simulated

The leading details of the vehicle simulation are presented in Appendix B.

The vehicle was a version of the Volkswagen Rabbit passenger automobile converted to electric battery drive, and further to one of two fuel cell/battery power systems (employing conventional lead-acid batteries, viz., Sears Die Hardtm units).

- Methanol Fuel — using a phosphoric acid fuel cell and reformer
- Hydrogen Fuel — using an alkaline fuel cell* fueled directly from the onboard hydrogen storage.

The methanol fuel cell system is essentially that described by Abens et al. and Onischak of Energy Research Corporation.¹ The fuel supply was an appropriate mixture of methanol and water. (Note: only the methanol per se is called out in the printouts provided.)

The hydrogen fuel cell system, as noted, was of the KOH alkaline electrolyte type specified only by a current-voltage characteristic curve (not provided here). The objective here was to capitalize on the availability of pure hydrogen fuel with the intrinsically higher efficiency alkaline cell (vis-à-vis the phosphoric acid cell, which operates optimally on hydrogen).

However, LASL investigators reported some impedance mismatch problems when the alkaline cell was integrated into the existing vehicle power system. The hydrogen runs presented were somewhat compromised for this reason. Unfortunately, the resources available did not permit this problem to be resolved for the purpose of this report.

Since no specific hydrogen containment systems were detailed for this investigation, a simplified but technically valid approach was used in which three (3) hydrogen/total hydrogen containment system mass fractions were used as inputs: 0.01, 0.05, and 0.22. These correspond

* Characteristics of this fuel cell were provided to LASL by BNL.

roughly to, respectively:

1. a state-of-the-art low-temperature metal hydride or high-strength pressurized gas storage container,
2. an advanced high-temperature metal hydride or a very sophisticated composite material pressure vessel, and
3. a demonstrated cryogenic liquid hydrogen vessel (viz., the MVE VLH-150 container²; see also Appendix D for current developments).

Two approaches were taken in making the runs: fixing maximum gross weight and fixing the stored energy amount.

The former tended to penalize the range and endurance of the 0.01 and, to a far lesser extent, the 0.05, mass-fraction hydrogen cases, although these had equivalent acceleration capabilities of the 0.22 hydrogen case and the methanol case.

The latter resulted in very high gross weights for the lower mass-fraction hydrogen cases. This resulted in low performance but yielded reasonable ranges. (However, the 0.01 hydrogen case was unable to follow the residential and metropolitan driving cycles.)

Findings

The results of the LASL driving cycle simulations are summarized in Table 4-4. Three hydrogen cases (equal stored energy/variable gross weight) and three methanol cases are included. A seventh gasoline case is included only for fuel operating cost comparison purposes. In this case, the gasoline costs are adjusted downward from the pump price to that equivalent to the hydrogen and methanol costs. (See explanatory notes.)

Also, it can be seen that the 0.010 hydrogen storage system case was unable to be operated on the residential and metropolitan driving cycles. This vehicle was simply too massive to provide the stipulated acceleration levels.

An interesting finding is that the fuel operating costs (¢/mile) for all cases are of the same general magnitude.

TABLE 4-4.

Comparison of Simulations of various cases of H₂ and Methanol fueled Fuel Cell/Battery Vehicle Systems in the Volkswagen "Rabbit" Vehicle Type. (Source: Dr. B. McCormick and Dr. D. Lynn, Los Alamos Scientific Laboratory, August 1979).

(Energy Storage Density of .220 is equivalent to present capability of Minnesota Valley Engineering Technology, .050 is equivalent to magnesium-titanium hydrides and best pressure cylinder technology, .010 is approximately equivalent to iron-titanium hydride storage technology.)

Run No.	1	2	3	4	5	6	7
Fuel	Hyd.	Hyd.	Hyd.	Meth.	Meth.	Meth.	Gasoline
Energy Storage Density, lb/lb fueled tank wt.	.220 Liquid	.050 Hyd	.010 Hyd	.833	.833	.833	.820(est)
Gross Vehicle Weight, lb	3472	3937	6337	3580	3580	3580	2900 (est)
Fuel Cell Type	Alk	Alk	Alk	Acid	Acid	Acid	-
WIDE OPEN THROTTLE	No. of Cells (Fuel Cell)	140	140	140	160	180	-
	10s, mph	29.9	27.4	20.2	30.0	33.0	-
	30s, mph	48.5	46.3	36.7	47.5	51.1	-
	100s, mph	56.5	55.5	50.2	53.5	57.3	-
	Max V, mph ¹	56.7	55.9	51.6	53.6	57.3	-
	Fuel Consumption, mi/lb _{H2} , mi/gal _{Meth}	23.9	22.7	17.8	21.6	21.4	-
	Net Battery Charge	D	D	D	D	C	-
	Fuel Cell Effic., avg. %	51.5	51.1	48.7	39.9	39.0	-
	Vehicle Range, mi	717	681	534	648	642	-
	Cost per mile (Hi), ¢	4.1	4.5	5.8	4.0	4.1	1.7 ² _{Fuel Cost Only}
	Cost per mile (Lo), ¢	3.6	2.2	2.8	2.2	2.2	1.7 ² _{Fuel Cost Only}
227R	Fuel Consumption, mi/lb _{H2} , mi/gal _{Meth}	19.3	16.9	* ³	11.1	18.4	-
	Fuel Cell Effic., avg. %	53.5	52.3	* ³	35.3	35.6	-
	Cost per mile (Hi), ¢	5.1	6.1	* ³	7.8	4.7	5.2 ⁴ _{Fuel Cost Only}
	Cost per mile (Lo), ¢	4.5	2.9	* ³	4.2	2.6	5.2 ⁴ _{Fuel Cost Only}
227M	Fuel Consumption, mi/lb _{H2} , mi/gal _{Meth}	14.9	12.2	* ³	9.3	15.9	-
	Fuel Cell Effic., avg. %	51.1	50.2	* ³	36.4	35.5	-
	Cost per mile (Hi), ¢	6.7	8.4	* ³	9.3	5.5	5.2 ⁴ _{Fuel Cost Only}
	Cost per mile (Lo), ¢	5.8	4.0	* ³	5.1	3.0	5.2 ⁴ _{Fuel Cost Only}

Table 4-4, Cont. Constant Values and Notes

Constant Values:

Atmospheric Density = 0.0616 lb/ft^3
Initial Battery Charge = 80%
Power @ .6 V = 20 Kw
Ampere Hours in Battery = 50
Cells in Battery = 48 (conventional lead-acid type)
Motors - 2 Baldors @ 10 HP rating
Current Limit = 200 amps
Transmission - EVAN @ 2800 rpm shift point
Rear End - 22 Diam at 4.148 final drive ratio
227 R - 227 Residential Driving Cycle
227 M - 227 Metropolitan Driving Cycle
For other details, see Appendix B

Notes:

- ¹ - Maximum velocity is without field current reduction which can increase operating rpm to 3000-4000 @ double power output. Vehicle could achieve speeds over 65 for limited time periods - equivalent to a "passing gear".
- ² - Assumes 40 miles per gallon @ \$1.00 per gallon - 4¢(Fed. Tax) -10¢(State average Tax) - 15¢ (Distribution and Station Operation costs) = 71¢ per gallon
- ³ - 0.01 energy storage density system, equivalent to Iron-Titanium Hydride, in Rabbit could not achieve required drive cycle velocity
- ⁴ - Assumes 30 miles per gallon, gas per ² above.

Fuel Costs:

Source: Cant, E.N., et al, Alternate Energy Sources for Non-Highway Transportation, Exxon Laboratories, Final Report, Contract No. DE-AC05-77CS05438, for U.S. D.O.E., 1979

Methanol from Coal - \$7.80 to \$14.40 per 10^6 Btu

Liquid Hydrogen from Coal - \$16.70 to \$19.20 per 10^6 Btu

Gaseous Hydrogen from Electrolysis - \$9.50 to \$19.50 per 10^6 Btu where the hydrogen is generated from utility electrical sources at high and low 1980 price estimates per kWhr.

All prices are estimated for 1980

In performing the analyses presented in Table 4-4 , the LASL investigators used a conservative approach in establishing their performance assumptions, e.g., available state-of-the-art component characteristics are assumed throughout. Further, the hydrogen-air fuel cell system does not represent an optimized configuration. For these reasons, the results shown are known to be conservative.³

To illustrate this, the energy requirements for the various driving cycles are notably on the high side.⁴ For example, the energy requirements for the 3937-pound vehicle (Table 4-4, column 2) on the J227R cycle are estimated as 502 Wh/mile. Calculations for an all-battery vehicle on a similar cycle weighing 3909 pounds resulted in 275 Wh/mile.⁵

Optimized fuel cell/battery powered vehicles could complete these cycles with considerable less energy expenditures. This particular area of study, i.e., the optimization of fuel cell/battery vehicle systems deserves high priorities in further design analysis and simulation efforts.

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APPENDICES

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APPENDIX A

Excerpt from:

"Fuel Cells for Electric Vehicles," by Karl V. Kordesch,
presented at the International Society of Electrochemistry,
28th Meeting, 18-23 September 1977

as reproduced in:

"Proceedings of the Fuel Cell in Transportation Applications
Workshop," Los Alamos Scientific Laboratory Conference
Proceedings, LA-7270-C, July 1978

Comment:

This paper excerpt provides a concise review of what
has been accomplished with demonstration vehicle systems
employing fuel cell and fuel cell/battery vehicles.

Not mentioned, however, is the MERADCOM fork lift
truck and the more recent LASL golf cart test unit discussed
in the text.

Figures and references presented are excerpted and
included here.

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Demonstration Vehicles

A. With Hydrogen Fuel Cells

In spite of the experimental nature of many fuel cell batteries, demonstration vehicles powered by them have provided much experience for future developments. One of the first vehicles was a tractor built by Allis-Chalmers Mfg. Co. in 1959. It was powered by a 15-kW H_2 - O_2 battery using asbestos separators to immobilize the KOH electrolyte. The current density was only 20 mA/cm², therefore the battery weight was 917 kg (19). The same company demonstrated operation of a golf cart and a lift truck, powered by a 3-kW hydrazine-oxygen fuel cell battery, in 1963 (20). In 1965 Shell Research Labs. in Thornton, England, operated a 5-kW H_2 -air fuel cell battery-powered small truck. Hydrogen was obtained by steam reforming of methanol (19).

Probably the most extensive study of a fuel cell-powered vehicle was done by General Motors (1965-66). A six-passenger van was selected for this project because it allowed room for instrumented experimentation. The motor was a 125-hp (13,700 rpm) three-phase, electronically controlled induction motor. The fuel cell battery (built by Union Carbide Corp.) consisted of a 32-module H_2 - O_2 battery with a nominal output of 32 kW and a peak power of 160 kW. Figure 6 shows a sketch of the "Electrovan" (21). The program demonstrated that fuel cell technology had reached a point (in 1965) where high output for vehicles was attainable. The total fuel cell power plant weight was 1500 kg (energy density: 10 kg/kW) and the performance concerning speed (115 km/h max) and acceleration (0 - 100 km/h in 30 sec) was satisfactory. Driving range of the vehicle was cryogenic hydrogen and oxygen was 250 km. However, evaluation tests also defined many points that were unsatisfactory: (1) heavy weight (100% overweight); (2) complicated start up and shutdown procedures; (3) use of cryogenic liquids (especially oxygen), and (4) short life of batteries, even when not used. It was considered necessary to operate with oxygen rather than air to obtain the top speed and the desired acceleration behavior.

A hybrid system consisting of a fuel cell battery in parallel with a lead-acid battery reduces weight, removes starting delays, allows the use of

air, and provides the possibility for intermittent operation of the fuel cell system, by keeping it deactivated when the vehicle is not in use. The accumulative operating life of the fuel cell (e.g., 5000 hours) is then the same as that of a combustion engine. The author built such a test vehicle (22) which proved all these points during urban driving over a period of four years (1971-75) for a total of 21,000 km. The same hydrogen-air battery would have lasted only 5000 hours ($\approx 1/2$ year) if kept continuously active. Figure 7 shows the principal circuit diagram of the hybrid power plant. The lead-acid battery in the front of the car consisted of seven 12-volt batteries (84 V, 90 Ah); weight: 150 kg; maximum power output: 20-30 kW (200 W/kg). Figure 8 shows the diagram of the 90-V hydrogen-air fuel cell battery capable of 6-kW continuous output. The vehicle was a four-passenger compact car (converted Austin A-40) with a curb weight of 1000 kg, complete with six steel cylinders (weight: 80 kg) and containing 25 m³ of hydrogen at 130 atm (equivalent to 45 kWh), thus assuring a driving range of 300 km. The energy density of the fuel cell system (total weight: 250 kg, including tanks) was 140 Wh/kg. During operation of the hybrid system there is fully automatic load sharing between the batteries. This load sharing can be described in a power or energy profile (6), which more than satisfies the demands for the commuter car listed in Table 1 and pictured in Fig. 3.

The improvement of the air electrode power output by a factor of two (from 100 to 200 mA/cm²) achieved within the past five years brings the fuel cell output to a level of 10 to 15 kW. This means saving 50% of the lead battery weight, perhaps indicating that a nickel oxide-hydrogen battery (23) would be a far better (lighter) choice than the lead battery, and would provide even higher peak currents putting less importance on energy density. This would also open up the field for exploring "internal hybrid" fuel cells (MeOx, C, air/KOH/ H_2) to allow even more weight and volume savings.

*Table 1 and Fig. 3 are not presented in this abridged version.

The advantages of a fuel cell-hybrid battery vehicle using compressed O_2 was extensively studied (8). The unavailability of a low cost, high power electrode at that time (1974) was probably the reason for choosing O_2 . Systems using hydrogen (as compressed gases) can be considerably improved if recent work on reversible storage of hydrogen in special alloys proceeds successfully (24). The use of liquid ammonia as a hydrogen source in combination with a catalytic decomposition unit also seems to be very practical (25).

B. With Liquid-Fuel Fuel Cells

With the exception of the previously mentioned vehicles (19, 20) which employed methanol (converted) and hydrazine cells only, all others used hybrid systems. In 1966, the author built a motorcycle system consisting of a 16-V, 800-W Union Carbide hydrazine-air battery and a powerful (2.5-kW) nickel-cadmium battery. The motorbike was able to cruise at 40 km/h and had a range of over 200 km on 4 liters of hydrazine monohydrate (2). In 1968, the US Army in cooperation with Monsanto Research Corp. developed a 28-V, 20-kW hydrazine-air battery for a 3/4-ton M-37 Army truck. A lead-acid battery was used to provide instant maneuverability (2). In operation, the specific power density was 100 W/kg. The practical energy density of the fuel ($N_2H_4 \cdot H_2O$) was assumed to be 1 kW/kg for purposes of calculating the vehicle's range.

Shell Research, Ltd. (England) developed hydrazine-air batteries since 1967 and achieved power densities of 150 W/kg. A passenger car (a converted DAF-44) with a weight of 1380 kg was powered by a hydrazine-lead hybrid system (26). The schematic diagram of this system is pictured in Fig. 9. The load sharing of the fuel cell and lead battery can be derived from Fig. 10. The car's performance in city traffic was similar to the gasoline version.

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Figure 6. General Motors Electrovan.

Figure 7. Principle Circuit of the Hybrid Powerplant of the Electric Car Built by the Author in 1970.

Figure 8. Diagram of a Hydrogen-Air Fuel Cell System Built by Union Carbide Corp. (1970).

Figure 9. Hydrazine-Air Powerplant of the Shell-DAF44 Electric Automobile (1972).

Figure 10. Load Sharing Diagram of the DAF 44 Hybrid Car.

APPENDIX B

B-I Methanol Example Run

B-II Liquid Hydrogen Example Run

Source: LASL, August-September 1979

Dr. Byron McCormick

Dr. David Lynn

APPENDIX B-I

METHANOL RABBIT VEHICLE SIMULATION RUN

```

*****
*
*
*   FUEL CELL - BATTERY HYBRID VEHICLE SIMULATION PROGRAM
*
*   LOS ALAMOS SCIENTIFIC LABORATORY
*
*   VERSION DATE 08/11/79 OKL
*
*
*****

```

ACID FUEL CELL/BATTERY ELECTRIC RABBIT

FILE NAME: RABBT7

BATTERY: 48 CELLS, 50AH, 4.8KWH (20HR), 55LB/KWH

FUEL CELL: 160 CELLS, 1.39 FT**2, 34LB/KW

P = $160 \times .6 \times 150 \times 1.39 = 20KW$

REMOVED UPPER CURRENT LIMITS ON FUEL CELL AND BATTERY
 THE LOWER FC AND BTRY CURRENT LIMITS ARE $I = 0$, $I = -5AH$
 BATTERY V IS A STRAIGHT LINE FROM $I = 0$ TO $I = 5 \times BAH$

IMIN = -50 AMPS

WEIGHT = 2350 - 257 + DRIVER + 1 PASSENGER + FC + BTRY
 + FUEL + FUEL CONTAINER

= $2093 + 150 + 150 + 580 + 264 + 243 = 3580$

POWERED BY 2 BALDORS, 10HP EACH

FUEL IS METHANOL, 6.75LB/GAL + 40LB TANK

$30 \times 6.75 + 40 = 243$

VRHO = .0616 LB/FT**3 (5000 FT, 25 C)

Re: Vehicle Weight Breakdown

2350 - 257 = Veh. Gross - Engine

243 = Fuel + Container

```

*****
*
*           RABBIT WITH 20KW FUEL CELL AND 5KWH BATTERY
*
*           WIDE OPEN THROTTLE ACCELERATION
*
*           RUN SUMMARY (ENGLISH UNITS)
*
*****

```

TIME (SEC)	5000.00	DISTANCE (MILES)	79.32
AVERAGE SPEED (MPH)	57.11	FINAL SPEED	57.20
AVE MOTOR RPM	3621.48	AVERAGE THROTTLE	.9999
INITIAL BATTERY CHARGE	.8000	FINAL BATTERY CHARGE	.6386
MIN BATTERY CHARGE	.6386	AT TIME	5000.00
TOTAL METHANOL (GAL)	3.71	AVE MILEAGE (MPG)	21.36
FUEL FOR RECHARGE	.12	RECHARGE TIME (SEC)	1952.23

	AVERAGE POWER OUT (HP)	AVERAGE CURRENT	AVERAGE EFFICIENCY
FUEL CELL	25.59	197.21	.3900
BATTERY (DIS)	.58	4.48	
BATTERY (CHG)	.00	.00	
SOURCE	26.17	201.69	
CONTROLLER	25.07		.9580
MOTOR	21.11	201.74	.8420
DRIVE TRAIN	18.86		.8935
SOURCE TO WHEEL EFF			.7207

	PEAK VALUE	TIME
VELOCITY	57.38	170.00
MOTOR POWER	39.32	11.00
FUEL CELL CURRENT	409.21	11.00
BATTERY DISCHARGE CURRENT	124.42	.10
BATTERY CHARGE CURRENT	0.00	0.00
SOURCE CURRENT	500.00	.10
MOTOR RPM	3636.62	170.00

```

*****
*
*           RABBIT WITH 20KW FUEL CELL AND 5KWH BATTERY
*
*           SAE J227 RESIDENTIAL DRIVING SCHEDULE
*
*           RUN SUMMARY (ENGLISH UNITS)
*
*****

```

TIME (SEC)	300.00	DISTANCE (MILES)	1.75
AVERAGE SPEED (MPH)	21.02	FINAL SPEED	0.00
AVE MOTOR RPM	1628.17	AVERAGE THROTTLE	.3516
INITIAL BATTERY CHARGE	.8000	FINAL BATTERY CHARGE	.7964
MIN BATTERY CHARGE	.7933	AT TIME	237.50
TOTAL METHANOL (GAL)	.10	AVE MILEAGE (MPG)	18.44
FUEL FOR RECHARGE	.01	RECHARGE TIME (SEC)	175.07

	AVERAGE POWER OUT (HP)	AVERAGE CURRENT	AVERAGE EFFICIENCY
FUEL CELL	9.27	69.68	.3560
BATTERY (DIS)	2.15	15.17	
BATTERY (CHG)	1.46	9.31	
SOURCE	8.48	75.54	
CONTROLLER	8.04		.9484
MOTOR	6.59	114.50	.8194
DRIVE TRAIN	5.95		.9027
SOURCE TO WHEEL EFF			.7015

	PEAK VALUE	TIME
VELOCITY	30.00	237.50
MOTOR POWER	30.97	20.77
FUEL CELL CURRENT	406.05	170.53
BATTERY DISCHARGE CURRENT	107.04	20.16
BATTERY CHARGE CURRENT	-13.01	199.00
SOURCE CURRENT	500.00	20.16
MOTOR RPM	2800.00	182.11

COMPLETED 2 DRIVE CYCLES.

```

*****
*
*          RABBIT WITH 20KW FUEL CELL AND 5KWH BATTERY
*
*          SAE J227 METROPOLITAN DRIVING SCHEDULE
*
*          RUN SUMMARY (ENGLISH UNITS)
*
*****

```

TIME (SEC)	300.00	DISTANCE (MILES)	2.09
AVERAGE SPEED (MPH)	25.05	FINAL SPEED	0.00
AVE MOTOR RPM	1849.23	AVERAGE THROTTLE	.3970
INITIAL BATTERY CHARGE	.8000	FINAL BATTERY CHARGE	.7755
MIN BATTERY CHARGE	.7730	AT TIME	250.00
TOTAL METHANOL (GAL)	.13	AVE MILEAGE (MPG)	15.93
FUEL FOR RECHARGE	.02	RECHARGE TIME (SEC)	343.81

	AVERAGE POWER OUT (HP)	AVERAGE CURRENT	AVERAGE EFFICIENCY
FUEL CELL	12.13	93.93	.3550
BATTERY (DIS)	1.88	14.44	
BATTERY (CHG)	2.89	9.27	
SOURCE	12.08	99.10	
CONTROLLER	11.31		.9363
MOTOR	9.17	129.12	.8110
DRIVE TRAIN	8.39		.9144
SOURCE TO WHEEL EFF			.6944

	PEAK VALUE	TIME
VELOCITY	45.00	100.00
MOTOR POWER	34.60	81.62
FUEL CELL CURRENT	406.80	170.53
BATTERY DISCHARGE CURRENT	107.04	20.16
BATTERY CHARGE CURRENT	-13.36	271.00
SOURCE CURRENT	500.00	20.16
MOTOR RPM	2852.22	100.00

COMPLETED 2 DRIVE CYCLES

APPENDIX B-II

LIQUID HYDROGEN RABBIT VEHICLE SIMULATION RUN

```

*****
*
*
*   FUEL CELL - BATTERY HYBRID VEHICLE SIMULATION PROGRAM
*
*   LOS ALAMOS SCIENTIFIC LABORATORY
*
*   VERSION DATE 08/11/79 DKL
*
*
*****

```

ALKALINE FUEL CELL/BATTERY ELECTRIC RABBIT

FILE NAME: RABBT2

BATTERY: 48 CELLS, 50AH, 4.8KWH (20HR), 55LB/KWH

FUEL CELL: 140 CELLS, 1.47 FT**2, 34LB/KW

P = $140 \times .605 \times 161 \times 1.47 = 20KW$

REMOVED UPPER CURRENT LIMITS ON FUEL CELL AND BATTERY
 THE LOWER FC AND BTRY CURRENT LIMITS ARE $I = 0$, $I = -BAH$
 BATTERY V IS A STRAIGHT LINE FROM $I = 0$ TO $I = 5 \times BAH$

IMIN = -50 AMPS

WEIGHT = 2350 - 257 + DRIVER + 1 PASSENGER + FC + BTRY
 + FUEL + FUEL CONTAINER

= 2093 + 150 + 150 + 680 + 264 + 135 = 3472

POWERED BY 2 BALDORS, 10HP EACH

FUEL IS LIQUID HYDROGEN, FUEL + CONTAINER WEIGHS 4.5LBS/LB OF H2

VRHD = .0616 LB/FT**3 (5000 FT, 25 C)

Re: Vehicle Weight Breakdown

2350 - 257 = Veh. Gross - Engine

Hydrogen Weight = 30 pounds

```

*****
*
*   RABBIT WITH 20KW FUEL CELL AND 5KWH BATTERY
*
*   WIDE OPEN THROTTLE ACCELERATION
*
*   RUN SUMMARY (ENGLISH UNITS)
*
*****

```

TIME (SEC)	5000.00	DISTANCE (MILES)	77.70
AVERAGE SPEED (MPH)	55.95	FINAL SPEED	55.76
AVE MOTOR RPM	3548.02	AVERAGE THROTTLE	.9999
INITIAL BATTERY CHARGE	.8000	FINAL BATTERY CHARGE	.3581
MIN BATTERY CHARGE	.3581	AT TIME	5000.00
TOTAL FUEL USED (LB)	3.26	AVE CONS (MI/LB)	23.85
FUEL FOR RECHARGE	.26	RECHARGE TIME (SEC)	3399.77

	AVERAGE POWER OUT (HP)	AVERAGE CURRENT	AVERAGE EFFICIENCY
FUEL CELL	23.43	185.65	.5153
BATTERY (DIS)	1.30	10.37	
BATTERY (CHG)	.00	.00	
SOURCE	24.73	196.02	
CONTROLLER	23.69		.9581
MOTOR	19.96	196.03	.8427
DRIVE TRAIN	17.80		.8917
SOURCE TO WHEEL EFF			.7199

	PEAK VALUE	TIME
VELOCITY	56.70	195.00
MOTOR POWER	31.89	2.63
FUEL CELL CURRENT	300.00	1.00
BATTERY DISCHARGE CURRENT	228.16	.10
BATTERY CHARGE CURRENT	0.00	0.00
SOURCE CURRENT	500.00	.10
MOTOR RPM	3593.84	195.00

```

*****
*
*      RABBIT WITH 20KW FUEL CELL AND 5KWH BATTERY
*
*      SAE J227 RESIDENTIAL DRIVING SCHEDULE
*
*      RUN SUMMARY (ENGLISH UNITS)
*
*****

```

TIME (SEC)	300.00	DISTANCE (MILES)	1.75
AVERAGE SPEED (MPH)	21.02	FINAL SPEED	0.00
AVE MOTOR RPM	1620.34	AVERAGE THROTTLE	.3479
INITIAL BATTERY CHARGE	.8000	FINAL BATTERY CHARGE	.7730
MIN BATTERY CHARGE	.7683	AT TIME	237.50
TOTAL FUEL USED (LB)	.09	AVE CONS (MI/LB)	19.34
FUEL FOR RECHARGE	.02	RECHARGE TIME (SEC)	374.49

	AVERAGE POWER OUT (HP)	AVERAGE CURRENT	AVERAGE EFFICIENCY
FUEL CELL	9.25	68.56	.5331
BATTERY (DIS)	4.54	31.95	
BATTERY (CHG)	2.24	13.68	
SOURCE	8.32	86.84	
CONTROLLER	7.89		.9479
MOTOR	6.49	113.46	.8220
DRIVE TRAIN	5.85		.9020
SOURCE TO WHEEL EFF			.7029

	PEAK VALUE	TIME
VELOCITY	30.00	134.00
MOTOR POWER	25.87	21.00
FUEL CELL CURRENT	284.44	170.41
BATTERY DISCHARGE CURRENT	225.64	20.16
BATTERY CHARGE CURRENT	-18.77	284.00
SOURCE CURRENT	500.00	20.16
MOTOR RPM	2800.00	31.83

COMPLETED 2 DRIVE CYCLES

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*****
*
*      RABBIT WITH 20KW FUEL CELL AND 5KWH BATTERY
*
*      SAE J227 METROPOLITAN DRIVING SCHEDULE
*
*      RUN SUMMARY (ENGLISH UNITS)
*
*****

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TIME (SEC)	300.00	DISTANCE (MILES)	2.08
AVERAGE SPEED (MPH)	24.96	FINAL SPEED	0.00
AVE MOTOR RPM	1840.22	AVERAGE THROTTLE	.4052
INITIAL BATTERY CHARGE	.8000	FINAL BATTERY CHARGE	.7191
MIN BATTERY CHARGE	.7150	AT TIME	250.00
TOTAL FUEL USED (LB)	.14	AVE CONS (MI/LB)	14.91
FUEL FOR RECHARGE	.05	RECHARGE TIME (SEC)	820.77

	AVERAGE POWER OUT (HP)	AVERAGE CURRENT	AVERAGE EFFICIENCY
FUEL CELL	11.40	89.49	.5109
BATTERY (DIS)	4.08	32.26	
BATTERY (CHG)	4.51	14.31	
SOURCE	11.85	107.44	
CONTROLLER	11.08		.9346
MOTOR	9.02	127.85	.8141
DRIVE TRAIN	8.24		.9139
SOURCE TO WHEEL EFF			.6953

	PEAK VALUE	TIME
VELOCITY	45.00	100.00
MOTOR POWER	28.97	82.11
FUEL CELL CURRENT	286.00	170.41
BATTERY DISCHARGE CURRENT	225.64	20.16
BATTERY CHARGE CURRENT	-21.10	271.00
SOURCE CURRENT	500.00	20.16
MOTOR RPM	2852.25	100.00

COMPLETED 2 DRIVE CYCLES.

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APPENDIX C

THE INFLUENCE OF FUEL CELL/BATTERY POWER SYSTEMS COSTS
ON OPERATING COSTS

and attachment:
FUEL CELLS FOR RAILROAD MOTIVE POWER SYSTEMS

THE INFLUENCE OF FUEL CELL/BATTERY POWER SYSTEMS COSTS ON OPERATING COSTS

The Baseline Case — The Passenger Automobile

The costs of operation of a typical sub-compact automobile in suburban driving have been estimated to be distributed as follows:

1.	Original Vehicle Depreciation	20.5%
2.	Maintenance, Accessories, Parts, and Tires	22.3%
3.	Gasoline and Oil (excluding taxes)	17.3%
4.	Garages/Parking, and Tolls	17.3%
5.	Insurance	13.4%
6.	State and Federal Taxes	<u>9.0%</u>
	TOTAL	approx. 100.0%

Source: Reference C-1.

These figures are for a 1974 vehicle operating on 1974 gasoline prices.

If we consider only a change of operation to an alternative fuel costing, for purposes of illustration, four (4) times the 1974 gasoline price, the overall cost of operation to the owner of the vehicle will increase to about 150% of the baseline gasoline cost of operation.

If we further propose that the more expensive fuel form will be used in a fuel cell/battery system costing \$120/kW, and compare this cost to a gasoline fueled internal combustion automobile engine (\$5-\$10/kW), the overall cost of operation, to the owner, will increase to a figure in the range of 300% to 400% of the baseline gasoline case.

In this situation, the purpose of the vehicle is to provide transportation to the owner. Thus, the result can be summarized by saying that cost of the service will be increased 300% to 400% in the hypothetical situation described above.

It is suggested that this is not the case where the service provided to the user, or customer, is delivered by a system where the service provided by the vehicle and fuel system comprises only a part of the total service system. Specific examples of such systems are truck, bus, rail, and automobile fleet systems.

Intercity Trucking

The equivalent distribution of costs, generally, for an intercity trucking company are, expressed as a percentage of total operating costs:

1.	Depreciation of Equipment	4.2%
2.	Maintenance, Accessories, and Parts	4.5%
3.	Fuel and Oil	4.7%
4.	Garage/Parking, and Tolls	0.5%
5.	Insurance	2.3%
6.	State and Federal Taxes	<u>3.6%</u>
	TOTAL	19.8%

Source: Reference C-2.

Bearing in mind also that a modern diesel engine designed for long-term operation in an intercity truck costs about \$50/kW, compared to the \$5-\$10/kW in the shorter-lived, gasoline fueled passenger car engine, the resulting impact on cost of the trucking service is significantly less than in the passenger car case. The change in the above cost component of the total operating costs of the truck line caused by substituting a fuel cell/battery power system and fuel at four (4) times the 1976 reported costs produce about a 20% increase in total operating costs (assuming \$120/kW for the fuel cell/battery).

Intracity and Intercity Buses

Both urban and intercity buses in the United States utilize high-speed diesel engines equivalent to those used in intercity trucking. It is anticipated that the same more favorable (than the case with private automobiles) fuel cell/battery power system cost-acceptability situation would also exist. However, no specific inquiry has been made to support this supposition.

* Based on a current tractor high-speed diesel engine cost of about \$15,000 for a 300 kW (400 hp) rating.

Rail Systems

While the budgetary categories used in railroad accounting do not permit an equivalent breakout of costs in the six categories discussed above, they can be estimated to comprise about 15% of total operating costs (see Reference C-3) compared to 20% for intercity trucks and 100% for personal passenger cars, as related above. (See also Reference C-4.)

In the rail case, the cost of a 2000-3000 hp diesel electric prime-mover system is roughly \$200/kW at the present time. This price exceeds the \$120/kW estimate we are using for our fuel cell and battery power system costs.

If we assume that rail service fuel cell/battery power systems costs the same as current rail diesel engine systems, i.e., \$200/kW (Reference C-5), the impact of fuel costs must still be considered. Novil (Reference C-4) has performed a comparative economic assessment of liquid hydrogen fueled rail motive power systems. This assessment examined the conversion of diesel systems to liquid hydrogen powered systems and included the impacts of additional servicing equipment together with a progressive 15-year phaseout of equipment over the useful lifetimes associated with rail motive power units of conventional design. The end result of the conversion produced a tariff increase, the increase in the cost of the rail service, of 3% to 4%.

Fleet Vehicles

While intercity trucks, urban buses, and rail motive power units are, in fact, fleet vehicles, this term is more often associated with fleets of sedans and light trucks in commercial service. The same effect produced by the fact that the costs of vehicle operation are only a portion of the total cost of operation of a service system in the intercity trucking and rail industries holds true for fleets of sedans and light trucks in commercial service. However, the percentage of the cost of fleet operations varies widely depending upon the nature of the firm using such vehicles. Two examples are a fleet of vehicles operated by an electric utility company and a fleet of vehicles operated by an organization engaged exclusively in industrial sales representation.

In the utility case, the effect of increased costs of vehicle operation on the total cost of electrical service will probably be less than the costs of operation of the vehicles owned by a sales representative firm on the total cost of sales made. However, at this writing, insufficient information is available to the authors to permit developing even a rough estimate of the costs impacts of the use of fuel cell/battery power systems and alternative fuel forms in these scenarios.

Comment

None of the above estimations include the amortization of research, development, and other costs associated with transition to these alternative power and fuel systems. On the other hand, no credit has been taken for the reduction of maintenance and repair costs that might be associated with fuel cell/battery power systems in comparison to internal combustion engines. To provide perspective, maintenance and repair costs are approximately equivalent to equipment depreciation costs in private automobiles and intercity trucking equipment systems. (See tables presented above.) In rail systems, these costs are about 15% of equipment depreciation costs (Reference C-3).

For additional information, a technical discussion of the possible use of fuel cells for railroad motive power systems is attached to this appendix.

It is also appropriate to note that it has been suggested that rail, intercity truck, and vehicle fleet operations, in that order, would be a logical sequence of pursuit toward the goal of eventual conversion of the passenger car to alternative fuel and engine systems.

However, this suggestion was not based upon the previously presented economic impact considerations. Rather, it was stated that this approach is more practical because of such considerations as:

- These systems have fewer fueling points requiring conversion
- A lesser number of vehicle systems are involved
- Single route or fleet conversion is an option
- Regional conversion can be progressively developed
- The risks involved in using equipment and fuels in demonstration operation would be reduced.

To these advantages must be added the economic advantages developed in the previous pages.

Recommendations

It is recommended that consideration be given to performing an adequately supported investigation of the alternative implementation strategies and the life-cycle economics of the use of fuel cell/battery systems in rail, intercity truck, bus, and fleet vehicle applications.

References Cited

- C-1. Transportation Energy Conservation Data Book, Transportation Energy Conservation Division ERDA, Report No. ORNL-5198, October 1976.
- C-2. Foster, R.W., Alternative Fuels and Intercity Trucking, U.S. Department of Energy, Report No. HCP/M3294-01, June 1978.
- C-3. Status of Railroads of Class I in the U.S., 1967-77, Statistical Summary No. 62, Economics and Finance Department, Association of American Railroads, September 1978.
- C-4. Novil, M., A Preliminary Comparative Economic Assessment of the Hydrogen Railroad System Concept, Institute of Gas Technology Project 9516, September 1977 (unpublished).
- C-5. Personal communication from R.F. Flinn, Morrison-Knudson, Inc., October 1979.

Attachment to Appendix C

FUEL CELLS FOR RAILROAD MOTIVE POWER SYSTEMS

Excerpts from

Cart, E.N., Jr., "Alternative Energy Sources for Non-Highway Transportation" (3 Volumes), Final Report Under DOE contract No. DE-AC05-77CS05438, by Exxon Research and Engineering Co., 1979

Part 1 from

Nicholson, E.W., "Possible Applications of Fuel Cells," (Section 5.1), Volume III-A — Appendices

Part 2 from

Percival, J., and Nicholson, E.W., "Railroads," (Section 7), Volume II — Technical Section

Comment

Exxon Research and Engineering Co., under DOE sponsorship, has recently completed a comprehensive study of alternative fuels for non-highway transportation systems, meaning essentially: rail, air, marine, and pipeline systems.

In this effort, fuel cell power was considered for each application area. In view of the present assessment's observation that the fuel cell/battery power system approach will permit electric propulsion to be able to compete in other areas than those now associated with all-battery electric vehicles, Exxon's views on the potential of the fuel cell as a railroad prime mover are of interest. Pertinent excerpts of their work is appended here.

(Part 1)

5.1.3.2.1 Characteristics of Diesel-Electrics

A diesel-electric locomotive consists basically of a large diesel engine with 16 to 20 cylinders which drives a generator to produce direct-current power. This DC power is distributed to series-wound DC traction motors at each wheel. In newer models, however, AC generators, or alternators, are being used in order to overcome the maintenance problems associated with the commutators and brushes required in DC generators. The AC current produced is rectified by solid-state units to provide the DC power for the traction motors. (5-21)

A 3300 HP (at the wheels) diesel-electric locomotive weighs 390,000 pounds, including 4000 gallons of fuel. The engine and alternator for this locomotive weigh 59,500 pounds. Based on an 85% efficiency from the engine output to the wheels, this represents a weight to power ratio of 15 lb./HP or 20 lb./kW. The corresponding volumetric ratios are about 0.3 cu. ft./HP or 0.4 cu. ft./kW.

5.1.3.2.2 Possibilities for Fuel Cells

It is not inconceivable that the above ratios could be achieved with fuel cells. As pointed out earlier, the Fuel Cell Powered Vehicle Workshop at Los Alamos in August, 1977 concluded that fuel cells including fuel processing equipment but with no power inversion facilities should be possible with 30 lb./kW and 1 cu. ft./kW ratios. (5-18) But, in this case, small units of only about 10 kW were being considered; the 2900 kW units required for a locomotive of this type should have much better power densities. For example, the power densities of the 10 MW fuel cell trailer in the design study on KOH electrolyte fuel cells Exxon Enterprises did for EPRI (5-9) were 6.3 lb./kW and 0.44 cu. ft./kW. These values do not include the weight and volume required for the fuel processing section. Further study will be needed in order to reach a more definitive conclusion regarding the technical feasibility of substituting fuel cells for the diesel engine-alternator-rectifier system in present-day diesel-electric locomotives.

A fuel cell system probably cannot be appreciably larger in volume than the present diesel-electric power equipment for the same horsepower rating because the overall dimensions of existing large diesel-electric locomotives are near the limits as constrained by tunnel and bridge clearances, radius of curvature of tracks, etc. on existing railroads. Space within the existing locomotive envelopes is already well utilized by required equipment and facilities. Improved fuel efficiency in a fuel cell powered unit could make additional volume available for the fuel cell by reducing the size of the fuel tank.

The allowable weight of a fuel cell system for the required power output needs to be studied further because a number of factors are involved which are associated with the design of the locomotive. One of these factors is "adhesion" between the drive wheels and the rails. Some locomotives are provided with ballast over some of the axles to improve adhesion. It seems possible that, in a modular fuel cell system, some of the fuel cell weight could be distributed to take the place of ballast, thus providing more allowable weight for the fuel cells.

In present locomotive design, the total load-pulling capacity, or tractive effort, is limited by the current-handling capability of the traction motors. More horsepower on board a given locomotive could, however, be used to operate the train at a higher speed. This could have a net economic advantage to the railroad.⁽⁵⁻²¹⁾ Even though the average daily speed of freight trains is only about 20 miles/hour (allowing for idle time waiting for reassembling of trains, switching, etc.),⁽⁵⁻²²⁾ the railroads seem to have little inclination to go to higher horsepower locomotives, as stated earlier.

Another aspect relating to adhesion could prove to be beneficial for fuel cell systems. In a diesel-electric locomotive, when slippage between wheels and track occurs for the limiting axle, power to all the axles must be reduced until the slippage stops. On electric locomotives with power from catenaries, control systems are possible so that power needs to be reduced only to that axle where slippage is occurring. It seems possible that a similar control system could be provided with fuel cells; since the system is modular in nature, separate power takeoffs could be arranged for various groupings of modules.

Fuel cells could have a significant advantage in fuel efficiency. The overall fuel efficiency of a diesel-electric when operating on productive load over an average load cycle is about 37%.⁽⁵⁻²¹⁾ But, diesel engines are most susceptible to damage, and thus increased maintenance costs and downtime, when they are being started up, as temperatures equalize; during this time, coolant and lubricant flows must be carefully monitored. In addition, the coolant is subject to freezing in cold weather. For these reasons, diesel-electric locomotives are generally kept running at idle continuously when they are not in load service, or in the shop for service. Road engines generally operate at idle 45-55% of the time, and switch engines 77%. For the road engines, the fuel consumed during idling amounts to about 6% of the total consumption, and reduces the overall fuel efficiency to about 33%. It is possible, however, that diesel efficiencies could be increased in the future through incorporation of bottoming cycles.

Fuel cell systems have been demonstrated to be easily and quickly started up and shut down, so continuing to run them at idle would not be necessary.* Assuming a 40% fuel efficiency can be obtained with a phosphoric

* The fuel reforming section would probably be maintained at temperature except for idling periods of greater than about 4 hours.

acid fuel cell system, and naphtha can be used as fuel, as shown in Table 5-1, this would reduce the fuel requirement on board the 3300 HP locomotive being considered from 4000 gallons to 3670 gallons, or a saving about 5400 pounds of weight and 45 cu. ft. of volume on board the locomotive, as well as reducing the operating costs for fuel.

Of course, the critical question is whether or not a fuel cell system could be economically competitive with diesel-electrics in railroad service. This is discussed in another section. It appears worthwhile to consider both the phosphoric acid fuel cell system for the 1978-85 period, and the molten carbonate system for later application. It is also conceivable that a KOH electrolyte system could be utilized if a feasible means can be devised to remove CO₂ from the fuel and air streams to the fuel cell.

(Part 2)

7.4.5 Fuel Cells

A separate appendix (7-II) has been devoted to a full discussion of fuel cells and their application to railroads. Below, is a condensation of the main points.

Fuel cells, while costly are no more so than several of the other engines considered in this study. Their efficiency is the highest, maintenance is reasonable, and they can be switched off to save fuel which other engines waste when idling. Finally, they may be capable of being electrically coupled to the wheel motors in a way that would save part of the losses which today's locomotives suffer in the alternator or direct current generators (viz., the 5% loss on freight engines and the 8% loss on switching locos).

A phosphoric acid cell looks as though it could break even with a diesel engine at a fuel cost of \$5/MBtu. Similarly a molten carbonate cell would break even at a fuel cost of \$4/MBtu.

The weight of the fuel cells is somewhat higher per horsepower than that of an equivalent diesel engine, but this would not necessarily incur any disadvantage.

	<u>Mass of Engine Plus Fuel, Lbs</u>	<u>% of Mass of Total Locomotive</u>
3000 HP diesel engine plus alternator rec- tifier and fuel	71,000	24
phosphate fuel cell plus voltage regulator plus fuel	88,000	30

A detailed design and engineering study is needed to determine the feasibility of using fuel cells on locomotives. Three important questions which have to be answered are:

1. Can the weight and volume requirement be accommodated? The volume of a phosphate cell system and its fuel is about 2600 ft³, compared with 1600 ft³ for a diesel/electric engine and its fuel. The weights and volumes of molten carbonate cells are not known at present.
2. Would the cells be adversely affected in performance by vibration, shocks, and tilting?
3. In the case of carbonate cells, operating at 1200°F, what problems of safety are there to be overcome?

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APPENDIX D

RECENT DEVELOPMENTS IN
CRYOGENIC HYDROGEN CONTAINER TECHNOLOGY
FOR VEHICLES

RECENT DEVELOPMENTS IN CRYOGENIC HYDROGEN CONTAINER TECHNOLOGY FOR VEHICLES

In the vehicle simulation section presented previously in this assessment report, on-board hydrogen storage systems were analyzed on the basis of weight of hydrogen contained expressed as a percentage of loaded container weight (i.e. container + fuel). The figures used were selected to provide representation of three classes of cases:

- Case 1 1% of loaded weight representative of iron-titanium hydride storage and low alloy steel pressure vessels
- Case 2 5% of loaded weight representative of magnesium-titanium hydride storage or very advanced, composite structure pressure vessels.
- Case 3 22% of loaded weight representative of cryogenic liquid hydrogen storage vessels.

While adequate literature is available descriptive of the first two system storage cases, such is not the case with the third case. Developments in this field have occurred with significant reductions to practice having been achieved only recently (Ref. D-1).

Fig. D-1 and D-2 illustrate cryogenic hydrogen storage tank systems that have been used to fuel internal combustion engines in vehicle applications. Additional tanks have been constructed and demonstrated in service (Ref. D-1). However, these tanks (Fig. D-1 and D-2) are representative of conversions of tanks originally designed for service with other cryogenics and which have been modified for hydrogen service.

An example of a cryogenic hydrogen delivery system designed specifically for application to vehicle fueling is the DFVLR system illustrated in Fig. D-3. This tank has the following general specifications:

Liquid Volume Capacity	150 liters (39 gallons)
Tank Mass, Empty	43 kilograms
Liquid Mass, Full	11 kilograms
Operating Pressure, (max)	8 bar
Heat Leakage	2.0 watts
Hydrogen Boiloff Rate	5 liters/day
Pressure Buildup Rate	0.4 bar/hr
Design Acceleration	30 g

A unique aspect of the DFVLR Tank System is the fact that an automated fueling system capable of supporting the use of the tank in vehicle applications has also been constructed by the DFVLR (Fig. D-4).

This system is contained in a single cabinet and is designed to load a cold tank in approximately five (5) minutes. The sequence of operation of this refueling, or "service station", includes verification of pressure, by vacuum, integrity of the connections made to the vehicle tank, filling valves sequencing, phase flow sensing, manual valve actuation checking, fill and vent line pump-out, and fueling cycle completion and "clear for disconnect" signalling.

The operation of this tankage and "service station" system is presently under investigation by the Los Alamos Scientific Laboratory under U.S. Department of Energy Contract W-7405-Eng-36. The project will involve the operation of an intermediate size Buick "Century" 4-door sedan with the DFVLR Tank and automatic fueling system (Reference D-2).

Costs

In addition to the technical problems implicit in the design of such fuel handling systems, there is a obvious cost impact on the total vehicle costs. Only one study has been accomplished to date (Ref. D-1) directed at estimating what the range of costs of such tanks would be. The general findings are briefly summarized in tables D-1 to D-3. Due to the relative immaturity of this technology, these estimates should be used with caution.

REFERENCES

- D-1 Escher, W.J.D., Survey of Liquid Hydrogen Container Technology for Highway Vehicle Fuel System Applications, U.S. Department of Energy, Report No. HCP/M2752-01, November 1978
- D-2 Stewart, W.F., "Liquid Hydrogen-Fueled Vehicle Project," Los Alamos Scientific Laboratory presentation at the DOE Automotive Technology Development Contractor's Coordination Meeting, 23-25 October 1979, Dearborn, Michigan.

Source: Beech

Figure D-1. Beech LNG Container Functional System Schematic Diagram

Loss rate — 1% per day
Capacity — 0.19 m³ (50 gallons) LH₂
Maximum working pressure — 207 kPa (30 usiq)
Empty weight — 42.6 kg (94 lb) (no top)
Top section — 2.72 kg (6 lb)

Source: LASL

Source: LASL

Source: Ref. D-1

Figure D-2. MVE Cryogenics VLH-150 Liquid Hydrogen Container Cross-Sectional View

Source: DFVLR

DFVLR LIQUID HYDROGEN CONTAINER
(TANK I) PLAN AND CROSS-SECTIONAL
VIEW DRAWINGS

Source: DFVLR

DFVLR CONTAINER FUNCTIONAL
SCHEMATIC DIAGRAM

Source: DFVLR

DFVLR LIQUID HYDROGEN CONTAINER
(TANK I) PLAN AND CROSS-SECTIONAL
VIEW DRAWINGS

Source: DFVLR

DFVLR TANK II
(ALUMINUM ALLOY CONSTRUCTION)

Source: Ref. D-1

Figure D-3.

Figure D-4. DFVLR Automated Fueling System. Dewar Supply Tank is on the Left, the Fueling System is in the Center and the DFVLR 32 Gallon Tank is on the Right. Tankage and Fueling System Have Been Operated in the F.R.G. in an Automotive Vehicle System. System is Presently at Los Alamos.

TABLE D-1 BASIC TANK SPECIFICATIONS

- (1) Liquid Hydrogen capacity--50 gallons (189 liters)
- (2) Nominal operating pressure, maximum--50 psig (3.4 bar, 345 kPa)
- (3) Some provision for active pressurization, e.g., resistance heater
- (4) No-loss pressure lock-up time, minimum--3 days
- (5) Configuration (geometry, orientation)
horizontal cylinder
- (6) Provision for liquid level gaging (type of system optional)
- (7) Fill and vent connections--standard type, adequate to meet any applicable governing regulations, existing or anticipated
- (8) Reasonably robust construction for normal, safe over-the-road highway service.

TABLE D-2

MANUFACTURERS' ESTIMATES FOR PRODUCTION COSTS OF VEHICLE LIQUID HYDROGEN CONTAINERS

(OEM price basis, 30,000 units, 1978 dollars¹)

Estimate A	\$1,640 ²
Estimate B	1,590 ³
Estimate C	950
Average	\$1,393

Notes: ¹Adjusted by an escalation factor of 1.06 applied to 1977 estimates.

²Extrapolated slightly from estimates for two smaller sized containers; "bare tank" equivalent estimate: \$1,430.

³Interpolated for 30,000 unit basis from three estimates between 1,000 and 100,000 units (see below).

TABLE D-3

A MANUFACTURER'S ESTIMATES FOR PRODUCTION COSTS OF VEHICLE LIQUID HYDROGEN CONTAINERS

(OEM price basis, 1,000-100,000 units, 1978 dollars¹)

Production-lot Assumed	Manufacturer's Estimate ²	Adjusted Estimate ³
1,000	\$2,330	\$2,040
10,000	1,840	1,610
100,000	1,430	1,250

Notes: ¹Adjusted by an escalation factor of 1.06 applied to 1977 estimates.

²Corresponds to "Estimate B" in previous table.

³Derived by applying the manufacturer's estimates (this table) to the average estimate from the previous table.

Source: Ref. D-1