

***PERP Report***

***Fuel Cells for Transportation***

**02/03S5**

*December 2003*



44 South Broadway, White Plains, New York 10601, USA  
Tel: +1 914 609 0300 Fax: +1 914 609 0399

This Report was prepared by Nexant, Inc. ("Nexant") and is part of ChemSystems Process Evaluation/Research Planning (PERP) Program. Except where specifically stated otherwise in this Report, the information contained herein is prepared on the basis of information that is publicly available, and contains no confidential third party technical information to the best knowledge of Nexant. The aforesaid information has not been independently verified or otherwise examined to determine its accuracy, completeness, or feasibility.

Neither Nexant, Subscriber, nor any person acting on behalf of either assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information contained in this Report. Nexant does not represent or warrant that any assumed conditions will come to pass.

The Report is submitted on the understanding that the Subscriber will maintain the contents confidential except for the Subscriber's internal use. The Report shall not be reproduced, distributed, or used outside Subscriber's organization without first obtaining prior written consent by Nexant. Each Subscriber agrees to use reasonable effort to protect the confidential nature of the Report.

# Contents

---

Section	Page
<b>Summary</b> .....	1
1.1 INTRODUCTION .....	1
1.2 FUEL CELL TECHNOLOGIES .....	2
1.2.1 Proton Exchange Fuel Cells (PEMC) .....	2
1.2.2 Solid Oxide Fuel Cells (SOFC) .....	4
1.2.3 Direct Methanol Fuel Cells (DMFC).....	5
1.2.4 Other Types of Fuel Cells and Summary.....	5
1.3 FUEL CELLS IN VEHICLES.....	6
1.4 FUEL SELECTION ISSUES .....	8
1.4.1 Hydrogen .....	8
1.4.2 Methanol .....	8
1.4.3 Gasoline .....	8
1.4.4 Ranking the Leading Fuels .....	8
1.5 THE HYDROGEN ECONOMY CONCEPT .....	9
1.6 FUEL DISTRIBUTION INFRASTRUCTURE .....	10
1.6.1 Hydrogen Fuel Distribution Infrastructure .....	10
1.6.2 Methanol Fuel Distribution Infrastructure .....	11
1.7 LEADING DEVELOPERS OF FUEL CELL VEHICLES (FCV) .....	12
1.8 FUEL CELL MARKET ASSESSMENT IN AUTOMOBILES .....	14
<b>2 Introduction</b> .....	18
<b>3 Fuel Cell Fundamentals</b> .....	19
3.1 TYPES OF FUEL CELLS .....	22
3.2 CHARACTERISTICS OF DIFFERENT TYPES OF FUEL CELLS .....	26
<b>4 Fuel Cell Technology</b> .....	27
4.1 PROTON EXCHANGE MEMBRANE FUEL CELLS .....	27
4.2 SOLID OXIDE FUEL CELLS .....	29
4.3 PHOSPHORIC ACID FUEL CELLS (PAFC) .....	31
4.4 MOLTEN CARBONATE FUEL CELLS (MCFC) .....	32
4.5 DIRECT METHANOL FUEL CELLS (DMFC) .....	33

4.5.1	Further Development Work on DMFC.....	34
4.6	COMPARISON OF FUEL CELL TYPES .....	37
<b>5</b>	<b>Fuel Cells in Vehicles .....</b>	<b>38</b>
5.1	OVERVIEW .....	38
5.1.1	Fuel Selection Issues.....	39
5.1.2	Fuel Development Strategies .....	41
5.1.3	The Hydrogen Economy Concept.....	42
5.1.4	Sourcing Hydrogen .....	43
5.1.5	FC Vehicles – Current Situation Analysis .....	43
5.1.6	Heavy Duty Vehicles (Trucks, Buses and Other).....	45
5.1.7	Costs (Materials and Operating) .....	45
5.1.8	Emissions Impacts .....	48
5.1.9	Focus of R&D .....	48
5.2	REVIEW OF FUEL CELL DEVELOPERS .....	51
5.2.1	Honeywell .....	51
5.2.2	Analytic Power Corporation .....	51
5.2.3	Avista Laboratories.....	51
5.2.4	Ballard Power Systems .....	51
5.2.5	DCH – Technology Hydrogen Sensors and Fuel Cells .....	52
5.2.6	Energy Partners.....	52
5.2.7	FuelCell Energy .....	52
5.2.8	Ford Motor Company TH!NK Technology .....	52
5.2.9	Global Thermoelectric .....	53
5.2.10	H Power Corporation .....	53
5.2.11	IdaTech Corp., Bend, OR .....	53
5.2.12	UTC Fuel Cells .....	53
5.2.13	Manhattan Scientifics, Inc .....	54
5.2.14	M-C Power .....	54
5.2.15	National Renewable Energy Lab (NREL), Colorado (PEM) .....	54
5.2.16	Netherlands Energy Research Foundation – ECN - (MCFC, SOFC, and SPFC) .....	54
5.2.17	Oak Ridge National Laboratory (ORNL), Tennessee.....	55

5.2.18	Pacific Northwest National Laboratory (PNNL), Washington (PAFC, MCFC, and SOFC) .....	55
5.2.19	Plug Power, L.L.C. ....	55
5.2.20	Proton Energy Systems .....	55
5.2.21	Rocky Mountain Institute, Colorado.....	55
5.2.22	Sandia National Labs, New Mexico .....	55
5.2.23	Siemens AG, Germany .....	56
5.2.24	Small-Scale Fuel Cell Commercialization Group, Oklahoma.....	56
5.2.25	Toyota Motor Corporation, Japan.....	56
5.2.26	University of California, Riverside.....	56
5.2.27	University of California, Davis, Institute for Transportation Studies	56
5.2.28	The U.S. Department Of Energy, Office of Fossil Energy\.....	57
5.2.29	Warsitz Enterprises, California.....	57
5.2.30	Siemens Westinghouse Power Corporation.....	57
5.2.31	AQMD's Technology Advancement Office .....	57
5.2.32	The Electric Power Research Institute (EPRI).....	57
5.2.33	California Energy Commission (CEC) .....	57
5.2.34	California Fuel Cell Partnership .....	58
5.2.35	Methanol Fuel Cell Alliance.....	58
5.2.36	National Energy Technology Laboratory .....	58
5.2.37	Gas Research Institute (now the Gas Technology Institute or GTI)..	58
5.2.38	Office of Fossil Energy, Department of Energy .....	58
5.2.39	The Office of Transportation Technologies.....	58
5.2.40	Solid State Energy Conversion Alliance (SECA).....	59
5.2.41	Fuel Cell Auto Standards .....	59
<b>6</b>	<b>Fuel Cell Market Assessment in Automobiles.....</b>	<b>60</b>
6.1	PEM .....	60
6.2	SOFC.....	64
6.3	DIRECT METHANOL FUEL CELLS .....	65
6.4	COMPETING TECHNOLOGIES .....	67
6.4.1	Conventional Internal Combustion Engines (ICEs) .....	67
6.4.2	Electric Hybrid Vehicles.....	67

6.4.3	Competition from Hybrid Vehicles .....	68
<b>7</b>	<b>Fuel Distribution Infrastructure .....</b>	<b>70</b>
7.1	HYDROGEN FUEL DISTRIBUTION INFRASTRUCTURE.....	70
7.2	METHANOL FUEL DISTRIBUTION INFRASTRUCTURE.....	70

<b>Appendix</b>		<b>Page</b>
<b>A</b>	<b>PERP Program Title Index (1992 - 2003).....</b>	<b>A-1</b>

<b>Figures</b>		<b>Page</b>
1.1	Fuel Cell Operation .....	1
1.2	Proton Exchange Membrane Fuel Cell (PEMC) .....	3
1.3	Schematic Diagram of Polymer Electrolyte Fuel Cell System Incorporating Fuel Processor .....	4
3.1	Fuel Cell Operation.....	20
3.2	Efficiency Operating Curves for FCs and ICEs.....	21
3.3	Fuel Cells versus Heat Engines.....	22
3.4	Fuel Cell Energy Carrier Quality/Convenience Spectrum.....	25
4.1	Proton Exchange Membrane Fuel Cell (PEMC) .....	27
4.2	Schematic Diagram of Polymer Electrolyte Fuel Cell System Incorporating Fuel Processor .....	28
4.3	Solid Oxide Fuel Cell (SOFC).....	30
4.4	Phosphoric Acid Fuel Cell (PAFC) .....	31
4.5	Molten Carbonate Fuel Cell (MCFC).....	32
4.6	Direct Methanol Fuel Cell (DMFC) .....	33
4.7	Bell Aerospace DMFC Developments.....	35
6.1	3-Cell Stack Test 7x7cm Cell, Polarization Curve .....	64

<b>Table</b>		<b>Page</b>
1.1	Characteristics of Fuel Cell Types .....	6
1.2	Ranking Of Key Characteristics Of Fuels For Vehicle Fuel Cells .....	9
1.3	Comparison of Methanol and Gasoline - Cost Plus Return, Delivered to Retail Service Station .....	12
1.4	Leading Fuel Cell Vehicle Developments .....	13
1.5	Current PEM Fuel Cell Performance Characteristics .....	14
1.6	Fuel Cell Stack Performance .....	15
1.7	Current Fuel Cell Production Cost.....	15
1.8	PEMFC Cost and Performance Requirements for Competitiveness .....	16
1.9	Projected Future PEM Fuel Cell Performance Characteristics.....	17
3.1	Characteristics of Fuel Cell Types.....	26

---

4.1	Fuel Cell Technologies and Attributes .....	37
5.1	Ranking Of Key Characteristics Of Fuels For Vehicle Fuel Cells .....	40
5.2	Leading Fuel Cell Vehicle Developments .....	44
5.3	Factory Costs for Gasoline PEMFC–ATR Propulsion Systems at Production Scale	46
5.4	Projected Comparative FCV Fuel Economies .....	47
5.5	Range Of Fuel Economy, Normalized for Gasoline FCV .....	48
6.1	Current PEM Fuel Cell Performance Characteristics .....	60
6.2	Fuel Cell Stack Performance .....	61
6.3	Current Fuel Cell Production Cost.....	61
6.4	PEMFC Cost and Performance Requirements for Competitiveness .....	62
6.5	Projected Future PEM Fuel Cell Performance Characteristics.....	63
6.6	NECAR 5 Performance Characteristics.....	66
7.1	Comparison of Methanol and Gasoline - Cost Plus Return, Delivered to Retail Service Station .....	72