300-Watt Power Source Development at the Jet Propulsion Laboratory

Presented by:
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Industry Day
Ft. Hood, Texas
April 12 to 14th, 2005

Presentation Outline

- DMFC Overview
- Program Discussion
- Overview of Power Source Design
- System Performance
- Analysis of System Performance
- Program Conclusions

Fuel Cell Team

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- Program Managers
  - R. Surampudi (Power Systems Manager)
  - R. Liang (Army Program Manager)
- Technical Team
  - T. I. Valdez (Principal Investigator)
  - S.R. Narayanan (DMFC Team Leader, Electrochemical Technologies Group Supervisor)
  - A. Kindler (Subsystem Design)
  - E. Baez (Packaging)
  - G. Klose (Mechanical Design)
  - A. Abatahi (Electronics)
  - M. Young (System Integration)
  - F. Clara (Lab Materials Processing)
  - P. Shakottai (Thermal and Fluids Modeling)
  - Samad Firdosy (Laboratory Support)
  - L. Slootsky (Laboratory Support)
  - I. Marr (Subsystem Testing)

Industry Partners

- Giner Electrochemical System, LLC
  - C. Cropley
  - Fuel cell stack hardware
- Donaldson Company Inc.
  - R. Canepa
  - Air filtration development
- Jerez Industries
  - R. Jerez
  - System component fabrication

DMFC Overview

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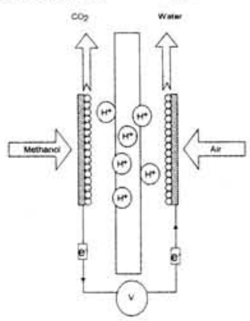
The Direct Methanol Fuel Cell

Direct Methanol Fuel Cell Reaction:

Anode: $CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$

Cathode: $3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$

Cell: $CH_3OH + 3/2O_2 \rightarrow CO_2 + 2H_2O$



DMFC Advantages

- Safety of handling a liquid fuel versus compressed gas fuel tank (i.e. Hydrogen)
- Low methanol concentration (<3%) in the "working" fuel loop

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The Benefits of A DMFC Power Source

	4 Battery Configuration		2 Battery Configuration	
	Battery	DMFC	Battery	DMFC
Mass (lb)	305	122.6	157	122.6
Volume (ft^3)	2.6	4.3	1.4	4.3
Energy (Whr)	4800	30000	2400	30000

- Substantial reduction in mass
- Increased energy capacity
- Increased operating time

Comparison based on information from TESCO using a 4-battery and 2-battery test configuration without recharging

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JPL Direct Methanol Fuel Cell Program Description

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Objective, Background and Requirements

Objective

- Develop direct methanol fuel cell technology and demonstrate a 300-Watt prototype power source.

Background

- The Army currently uses four deep cycle marine batteries to provide auxiliary power to armored vehicle external test instrumentation. The batteries mass is 138 kg (305 lb) and are limited to 8 hours of operation without recharging.

Summary of Requirements

- Power 300 W (Continuous)
- Run Time: 100 hr (Continuous)
- Energy: 30,000 Whr
- Target Mass: 36 kg (80 lb) (Including Fuel)
- Other Attributes:
  - Rapid Startup
  - Field Refueling for Extended Operation
  - No Recharge Time
  - Quiet
  - Low Thermal Signature

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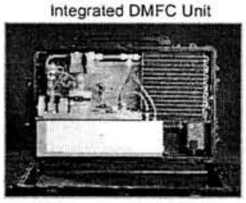
Summary of Accomplishments

Goal:
Develop a 300 Watt DMFC Power Source for powering test instrumentation on Armored Vehicles

Integrated DMFC Unit



- Developed A 300-Watt DMFC based power source design that can deliver 100hr of continuous operation has been designed and integrated
- The CBE figures of merit for this power source are 540 Whr/kg and 243 Whr/L for the specific power density and volumetric power density respectfully
- Scaled up cells from 25-cm^2 active area to 80 cm^2
- A five-cell stack has been scaled up to 80 cells and was demonstrated to deliver 370 Watts during bench testing
- Short stack testing reveal ruthenium dissolution into the polymer electrolyte membrane but did not have an impact on cell electrochemical performance
- Demonstrated autonomous operation capability of a complete fuel cell system in a box
- Operated continuously at a net output of 50 Watts for 8 hours
- Operated test instrumentation hardware (60 to 70 Watts) for 0.5 hours

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Future Development

- A 300-Watt DMFC system design has been completed
- The functionality of this system was demonstrated
- System design challenges and issues have been identified
- Industry members should develop this system into a pre-production prototype
- JPL's future role will be to assist the US Army with technical support to facilitate the delivery of a pre-production prototype power source

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Overall DMFC System Design

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Requirements

- Power Source:
  - Power 300 W (Continuous)
  - Run Time: 100 hr (Continuous)
  - Energy: 30,000 Whr
  - Target Mass: 36 kg (80 lb) (Including Fuel)
  - System Startup: Instantaneous when ambient temperature is greater than 5 °C (41 °F)
  - Field refueling
- Operational Environment:
  - Military war simulations
  - Air Quality: High dust concentration, 20 times zero visibility (~ 5 gm/m2 of ACS Coarse 30 microns dust)
  - Air Temperature: -17 to 45 °C (113 °F)
  - Relative Humidity: 0%
  - Attitude Sensitivity: +/- 45° to vertical
  - Unit must be protected during wash rack cycle.
- Shock and Vibration:
  - Survive a three-foot drop on concrete
  - MIL-STD-810

Requirements for the pre-production prototype to be finalized by the Army

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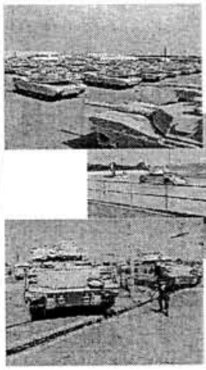
Technical Challenges



- Key Technical Challenges
  - Meeting environmental requirements
  - Continuous operation in thermal and water balance
  - System size and volume with contained fuel
  - Ruggedized operation
  - Safety of methanol handling
- Challenges to be addressed
  - Cost Effective Membrane Electrode Assembly (MEA) and System Fabrication
  - Power Source Longevity
  - Attitude Insensitive Operation
  - Ruggedized operation

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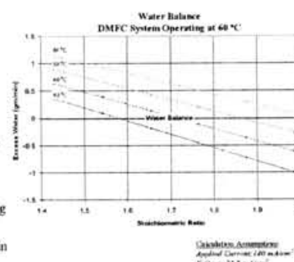
Challenges Resulting from Environmental Temperature

- Power Source Environmental Operating Temperature and Humidity: 45 °C, 0% RH
- At 0% RH, MEA operating stoichiometry will define system volume
- An airflow stoichiometry in the range of 1.7 to 1.8 is required for a DMFC stack, operating at 60 °C, without an exhaust condenser, to operate in water balance in 0% RH
- The smaller the temperature difference between the system operating temperature and the environmental temperature, the larger the radiator surface area required for cooling
- A DMFC-based power source operating at 60 °C in an ambient environment of 45 °C allows for only a 15 °C differential in temperature and results in an increased radiator size.



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Stack Design Challenges

- Operating Temperature
  - Heat rejection: Environmental temperature 45°C
  - Water balance: MEA operation at low airflow is required to maintain a water balance without the use of a condenser
- Orientation Sensitivity
  - Efficient product water removal is required during operation
  - Stack pressure drop, specifically the cathode pressure drop should be minimized to reduce ancillary power demand
- Stack Sizing
  - Sized to required power output, system ancillaries and power conditioning
  - Stack operating voltage should be selected to match with a higher efficiency power converter

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Electronics Subsystem Challenges

- Methanol Concentration Control
  - Operation time: 100 hours
  - *"in-field"* refueling required
  - Active concentration control via a methanol sensor is suggested
- System Startup
  - Instant startup
  - 15 minute startup from 5°C acceptable
- Power Management
  - Power source is required to be load following
  - Stack voltage should be controlled from spiking to protect electronics
- Ancillary power demand
  - Must reduce power required by ancillary to increase system operating efficiency
- Electronics Survivability
  - Electronics should be designed to operate at the maximum power source enclosure operating temperature
  - A minimum temperature of 60 °C is suggested
  - Electronics ruggedization

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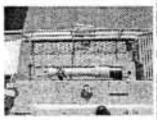
Operational Challenges

M1A2 Abrams (http://www.army-technology.com/projects/abrams/)

Abrams Commanders Accessory Box (M1A1, M1A2, and M1SEP)



M1A1 Abrams Rear Bustle Rack

Bradley Fighting Vehicle Bustle Rack

- System is required to operate "in-the-field"
- System should be insensitive to:
  - Vehicle Exhaust
  - Battlefield Contaminants
- System is configured to fit the Abrams rear bustle rack
- System can be configured to fit the Abrams commanders accessory box
- System redesign required to fit the Bradley fighting vehicle

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Overview of the DMFC System Design

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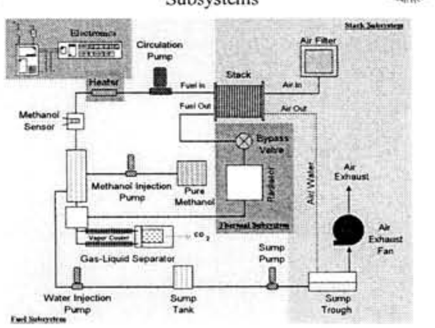
Subsystems



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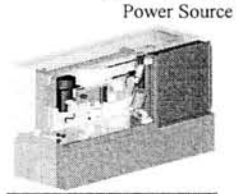
300W Direct Methanol Fuel Cell Power Source Specifications



System Specifications

Electrical
- Output Voltage: 24 V
- Power: 300 W
- Max Current: 12.5 A

Physical

Power Source
- Dimensions: 31.5 in x 20.7 in x 11.5 in
- Mass: 55.6 kg (122.6 lb)
- Volume: 123 L (4.3 ft³)
- Figures of Merit: 539.5 Wh/kg, 245 Wh/L

Fuel Cell System
- System Mass: 17.7 kg (39 lb)

Fuel Tank
- Fuel: Methanol(Supplied from internal fuel tank)
- Capacity: 30000 Whr
- Tank Volume: 32 L (1.1 ft³)
- Fuel Mass: 23.2 kg (35.5 lb)

Operational Environment
- Air Quality: High dust concentration, 20 times zero visibility (~5 gm/m³ of ACS Coarse 30 microns dust)
- System Startup: Instantaneous when ambient temperature is greater than 5 °C (41 °F)
- Wet Storage: 5 to 70 °C (158 °F)
- Air Temperature: -17 to 45 °C (113 °F)
- Attitude Sensitivity: +/- 45° to vertical
- Shock and Vibration: Survive a three-foot drop on concrete.
- Unit must be protected during wash rack cycle.

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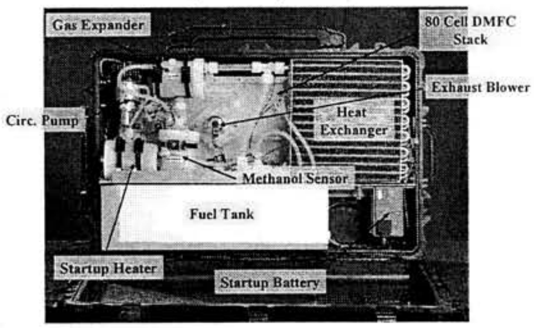
System Integration



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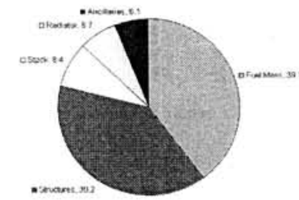
Component Percent of Power Source Mass



- The fuel mass and structures represent 80% of the power source mass
- A DMFC power source can achieve the highest energy density when the fuel mass represents a large fraction of the total system mass

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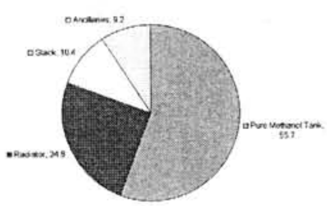
Component Percent of Power Source Volume



- System operating temperature and operating environment have a clear impact on radiator volume

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System Demonstration

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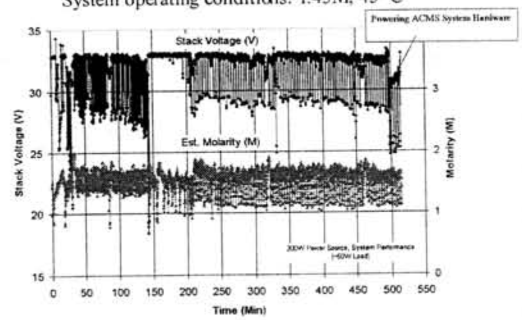
Power Source Performance, System operating conditions: 1.45M, 45 °C



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Results and Observations from the System Demonstration

- During the demonstration, the power source operated autonomously with the operating logic being driven by an external computer.
- The system started up in 18 minutes during the system demo
- The stack output power was over 150 Watts and the system delivered an output power of 50 Watts for over 8 hours. The power output was lower than expected
- After 8 hours of operation, ACMS systems electronics, which consumed approximately 70 Watts, were operated for half an hour.
- During the 8.5 hour continuous test, the system consumed approximately 1.3 L of pure methanol resulting in a fuel to electrical energy conversion efficiency of 7%. This value of system efficiency is to be expected considering that the system was not operating at its optimum power output and that 60% of the output from the stack was consumed in running the ancillaries.
- Water accumulation was noticed in the stack exhaust manifold. The water accumulation was a result of the air diffuser on the stack exhaust side saturating with water and a stack leak rate that was greater than the designed volumetric pumping speed of the sump pumps. The test was concluded because of water accumulation in the stack exhaust manifold.

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System Demonstration Summary

- After the system demonstration, the program focused on performance recovery
- Fault-tree analysis was performed on the system
- The fault-tree analysis revealed that cathode flooding was the primary reason for system performance decline
- The experiments performed for the fault-tree analysis were:
  - Stack test-stand testing
  - Stack tear down
  - Advanced single cell MEA testing
- The conclusions from the analysis of system performance defined by the fault tree are:
  - Fluid accumulation in the stack to be addressed by design changes
  - Stack leakages attributed to poor sealing
  - System performance decline was caused by cathode flooding
  - Ruthenium migration from the anode to the cathode of the MEAs manifested itself as cathode flooding
  - Commercial platinum-ruthenium catalyst appear to be stable during fuel cell operation

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Analysis of System Performance

Stack Testing

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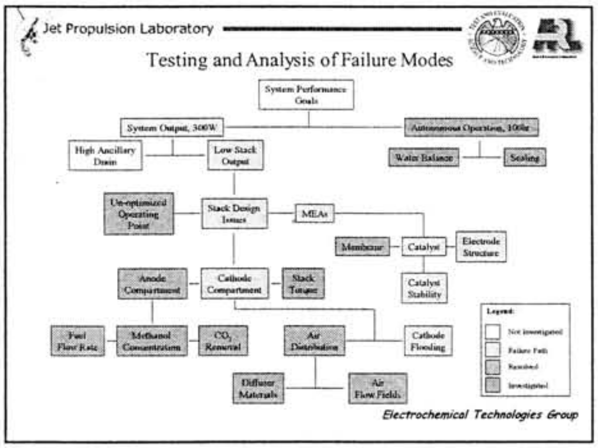
Jet Propulsion Laboratory
Testing and Analysis of Failure Modes
System Performance Goals
System Output, 300W
Autonomous Operation, 100hr
High Ancillary Drain
Low Stack Output
Water Balance
Sealing
Un-optimized Operating Point
Stack Design Issues
MEAs
Membrane
Catalyst
Electrode Structure
Catalyst Stability
Anode Compartment
Cathode Compartment
Stack Torque
Fuel Flow Rate
Methanol Concentration
CO2 Removal
Air Distribution
Cathode Flooding
Diffuser Materials
Air Flow Fields
Legend:
Not investigated
Failure Path
Resolved
Investigated
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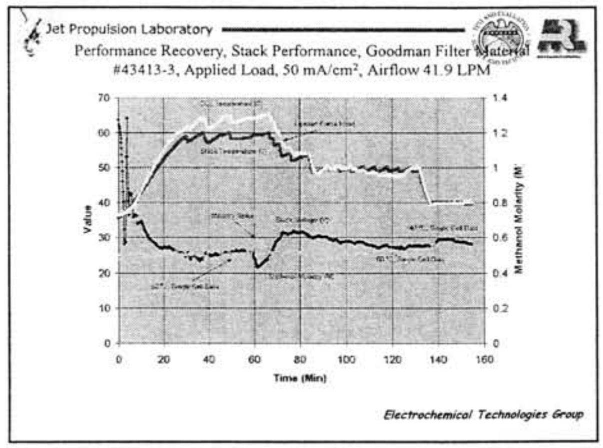
Jet Propulsion Laboratory
Performance Recovery, Stack Performance, Goodman Filter Material #43413-3, Applied Load, 50 mA/cm², Airflow 41.9 LPM
Value
Methanol Molarity (M)
Time (Min)
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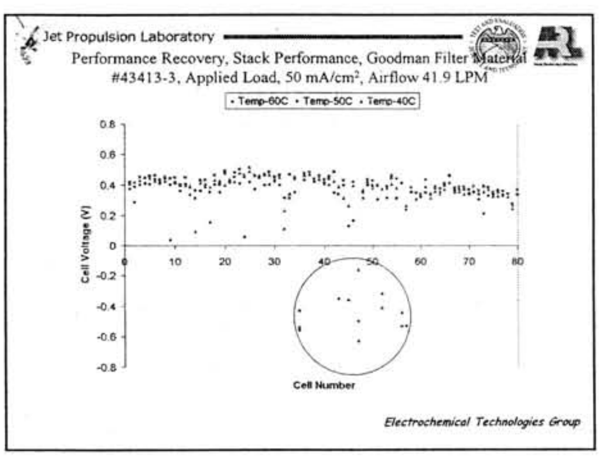
Jet Propulsion Laboratory
Performance Recovery, Stack Performance, Goodman Filter Material #43413-3, Applied Load, 50 mA/cm², Airflow 41.9 LPM
Temp-60C
Temp-50C
Temp-40C
Cell Voltage (V)
Cell Number
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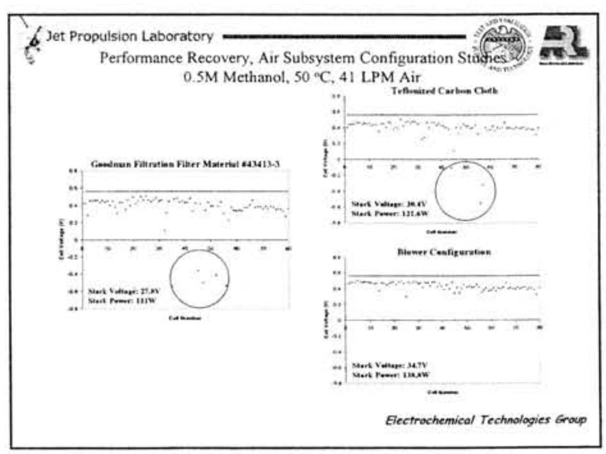
Jet Propulsion Laboratory
Performance Recovery, Air Subsystem Configuration Studies
0.5M Methanol, 50 °C, 41 LPM Air
Teflonized Carbon Cloth
Goodman Filtration Filter Material #43413-3
Blower Configuration
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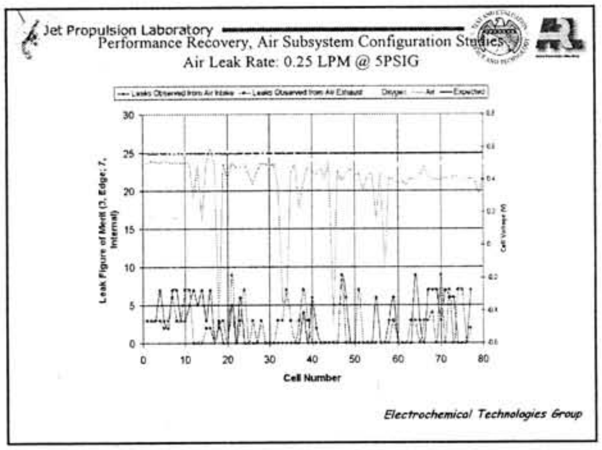
Jet Propulsion Laboratory
Performance Recovery, Air Subsystem Configuration Studies
Air Leak Rate: 0.25 LPM @ 5PSIG
Leak Figure of Merit (3, Edge; 7, Internal)
Cell Number
Cell Voltage (V)
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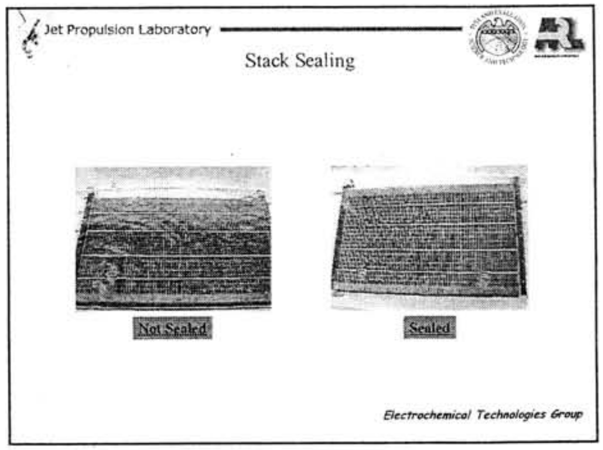
Jet Propulsion Laboratory
Stack Sealing
Not Sealed
Sealed
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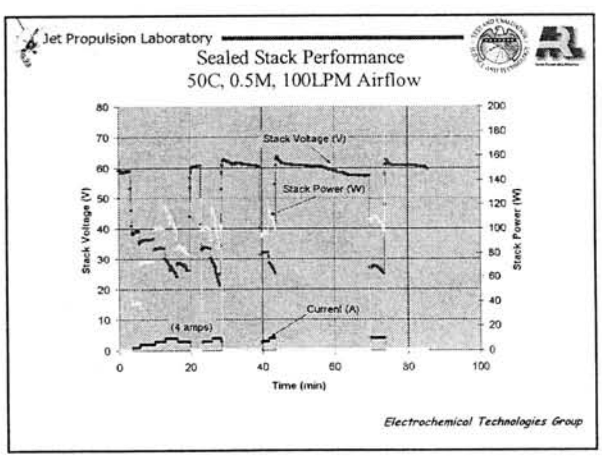
Jet Propulsion Laboratory
Sealed Stack Performance
50C, 0.5M, 100LPM Airflow
Stack Voltage (V)
Stack Power (W)
Current (A)
(4 amps)
Time (min)
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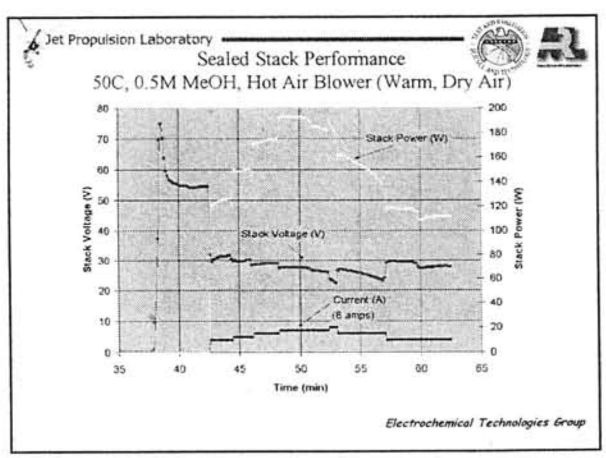
Jet Propulsion Laboratory
Sealed Stack Performance
50C, 0.5M MeOH, Hot Air Blower (Warm, Dry Air)
Stack Power (W)
Stack Voltage (V)
Current (A)
(8 amps)
Time (min)
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Analysis of System Performance

Stack Teardown

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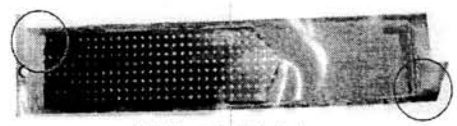
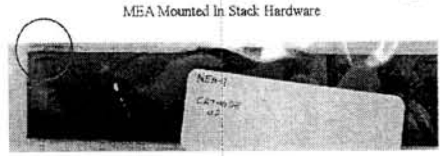
Discolored MEAs



MEA Mounted In Stack Hardware



MEA Stored in Plastic Bag

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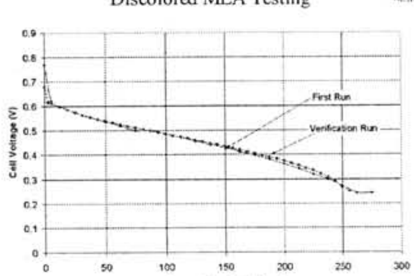
Discolored MEA Testing



- No Impact on MEA performance is apparent for discolored MEAs

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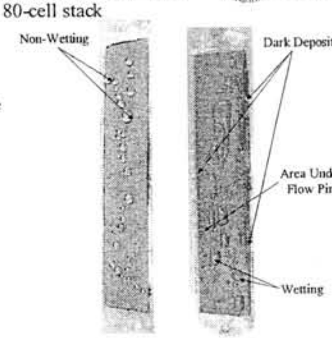
Observations on MEAs from the 80-cell stack

- Cathodes of MEAs from the stack exhibited increased wettability compared to a "fresh" MEA
- Patches of dark gray "deposits" found on various parts of the cathode
- The areas with dark deposits were more wettable than the lighter areas
- Several representative MEAs showed the same type of cathode changes
- Areas under the flow field pins remained "non-wettable"
- Flow field impressions were light and did not appear to damage the cathode papers



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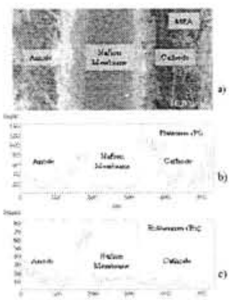
EDAX Analysis



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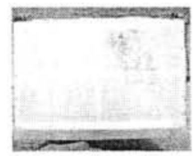
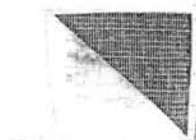
Diffuser Cloth





Brownish black ruthenium oxide precipitated at the cathode is washed down by water and absorbed on diffuser.

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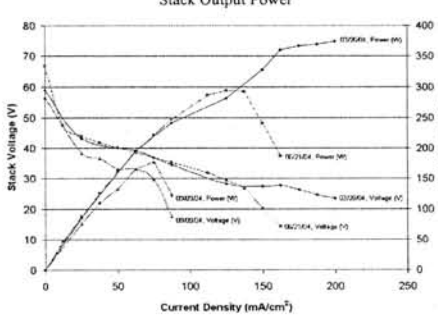
Impact of Stack Performance Decline on Stack Output Power



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Analysis of System Performance

Advanced MEA Studies

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Advanced MEA Studies

- Objective: To determine the stability of platinum-ruthenium catalyst and effect of carbon paper Teflon content for DMFC operation
- MEA Compositions
  - MEA# 012005, Anode: JPL, Cathode: 15% Teflon
  - MEA# 012505, Anode: Johnson Matthey, Cathode 15% Teflon
  - MEA# 012805, Anode: Reduced Johnson Matthey, Cathode 15% Teflon
  - MEA# 012905, Anode: Johnson Matthey, Cathode 5% Teflon (Standard)

All MEAs were fabricated with the same painting technique, catalyst loadings and hot-press conditions

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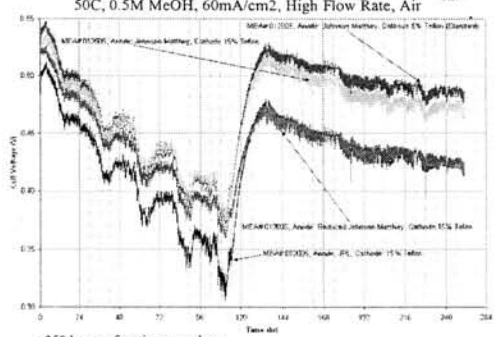
Ru Migration Studies, 250-hr Durability Test
50C, 0.5M MeOH, 60mA/cm2, High Flow Rate, Air



•250 hours of testing complete

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Post 250-hr Durability Testing Performance Summary

MEA Number	Formulation	Performance Decline (mV)		Rate of Decay (V/hr)	
		50 mA/cm^2	100 mA/cm^2	50 mA/cm^2	100 mA/cm^2
MEA# 012005	Anode: JPL, Cathode: 15% Teflon	48	150	0.00019	0.0006
MEA# 012505	Anode: Johnson Matthey Cathode: 15% Teflon	6	67	0.00002	0.00027
MEA# 012805	Anode: Reduced Johnson Matthey Cathode: 15% Teflon	30	107	0.00012	0.00043
MEA# 012905	Anode: Johnson Matthey Cathode: 5% Teflon (Standard)	6	96	0.00002	0.00038

- MEAs fabricated with the commercial Johnson Matthey catalyst showed the least performance decline
- The MEA fabricated with the reduced Johnson Matthey anode catalyst, MEA# 012805, performed similar to the MEA fabricated with the JPL catalyst, MEA 012005
- The test standard, MEA# 012905, performed the best during the durability experiments
- The rate of voltage decay for all MEAs tested is similar to values observed in the past

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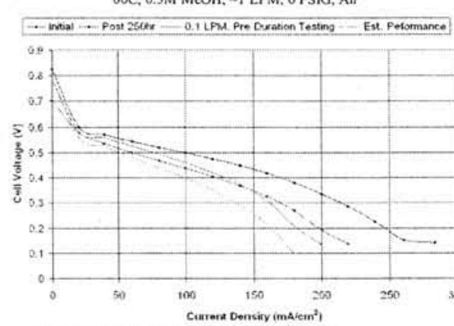
MEA Analysis - MEA 012005, JPL-Anode, 15-Cathode
60C, 0.5M MeOH, ~1 LPM, 0 PSIG, Air



•Lower operating currents post 250-hours of testing

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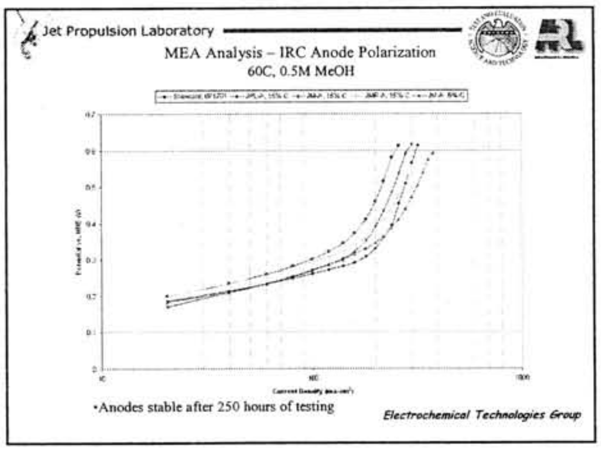
Jet Propulsion Laboratory
MEA Analysis – IRC Anode Polarization
60C, 0.5M MeOH
•Anodes stable after 250 hours of testing
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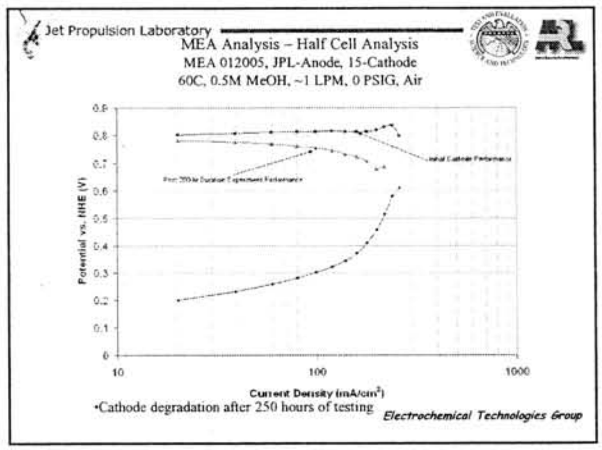
Jet Propulsion Laboratory
MEA Analysis – Half Cell Analysis
MEA 012005, JPL-Anode, 15-Cathode
60C, 0.5M MeOH, ~1 LPM, 0 PSIG, Air
Potential vs. NHE (V)
Current Density (mA/cm²)
10
100
1000
•Cathode degradation after 250 hours of testing
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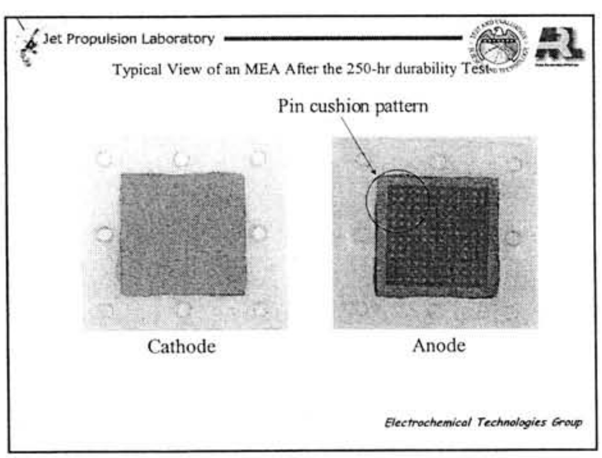
Jet Propulsion Laboratory
Typical View of an MEA After the 250-hr durability Test
Pin cushion pattern
Cathode
Anode
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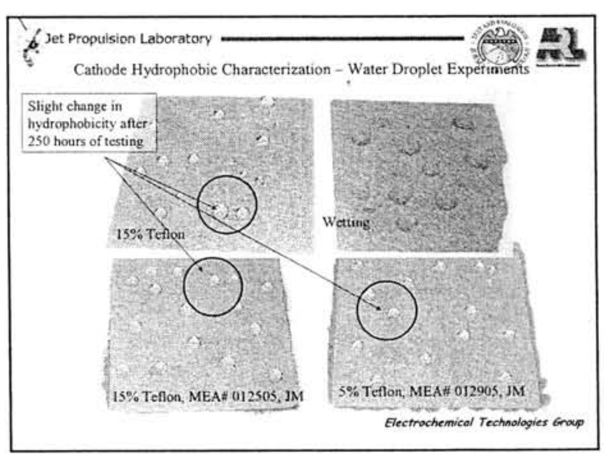
Jet Propulsion Laboratory
Cathode Hydrophobic Characterization – Water Droplet Experiments
Slight change in hydrophobicity after 250 hours of testing
15% Teflon
Wetting
15% Teflon, MEA# 012505, JM
5% Teflon, MEA# 012905, JM
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Durability Test Summary

- Four MEAs have completed durability testing in excess of 250 hours
- The cells were disassembled and individually tested in the single cell test stand
- Testing in the single cell test stand has revealed irreversible voltage decay on the cells
- The voltage decay rate was found to be in the range of 0.0006 to 0.0002 V/hr at 100mA/cm^2 which is in the range previously determined for MEAs fabricated in a similar fashion
- The voltage decay resulted in a an average decline of cell power of 20% at a 100 mA/cm^2
- EDAX analysis performed on the MEAs has shown that the commercial platinum-ruthenium catalyst is stable during DMFC operation

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Program Conclusions

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Power Source Testing Conclusions

- A 300W DMFC based power source design that can deliver 100 hours of continuous operation has been designed and fabricated
- The CBE figures of merit for this power source are 540 Whr/ kg and 243 Whr/ L for the specific power density and volumetric power density respectfully
- A five-cell stack has been scaled up to 80 cells and was demonstrated to deliver 370W
- Demonstrated autonomous operation capability of a complete fuel cell system in a box
- Operated continuously at a net output of 50 Watts for 8 hours
- Operated test instrumentation hardware for 0.5 hours
- Stack performance decline due to cathode flooding and ruthenium dissolution and thus limited power source output

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Recommendations

- **MEAs:** DMFC Membrane Electrode Assemblies (MEAs) should be developed that can operate for duration greater than 5000 hours with less than a 10% decline in power output
- **Stack Subsystem:** A stack should be designed that can address reactant avaliability to the MEAs electrodes during in-operation and limit shunt currents
  - The externally manifolded stack design limited orientation sensitivity, complicated water collection and exposed the MEA to an over abundance of oxygen
  - The MEAs access to oxygen, particularly at the cathode, contributed to ruthenium dissolution from the anode
  - The current collection/water collection scheme allowed the system to sustain shunt currents which also contributed to ruthenium dissolution from the anode
  - Water accumulated at the manifolds during the system demonstration that blocked uniform airflow to portions of the stack and may have contributed to shunt currents
- **Fuel Subsystem:** The gas liquid separator (GLS) should be designed to allow for better gas bubble (from heating and liquid flow) rejection
  - The GLS design limited the fuel liquid flow rate by restricting liquid flow via gas accumulation
  - During startup, bubbles could accumulate in the heating module and stop fuel circulation
- **Electronics Subsystem:** Purchase or fabricated a power converter with an input voltage range that spans the stack operating voltage range
  - The system power converter had a limited input voltage range of 18 to 36 volts
  - The stack voltage could rise to as high as 64 volts during load changes

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Acknowledgements

The work presented here was carried out at the Jet Propulsion Laboratory, California Institute of Technology for the National Aeronautics and Space Administration. This research was sponsored by Ms. Lisa Davis from the Office of the Director, Operational Test and Evaluation, was managed by Dr. George Shoemaker, Executive Agent for Embedded Instrumentation projects, and Mr. Henry C. Merhoff of the US Army Operational Test Command, Ft. Hood. Dr. Stephen Zakanycz of Institute for Defense Analyses provided both technical and programmatic consulting assistance to this program.

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