Hydrogen-Oxygen PEM Regenerative Fuel Cell Energy Storage System

David J. Bents and Vincent J. Scullin
Glenn Research Center, Cleveland, Ohio

Bei-Jiann Chang, Donald W. Johnson, and Christopher P. Garcia
QSS Group, Inc., Cleveland, Ohio
Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA’s scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA’s institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA’s counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA’s mission.

Specialized services that complement the STI Program Office’s diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:


- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076
Hydrogen-Oxygen PEM Regenerative Fuel Cell Energy Storage System

David J. Bents and Vincent J. Scullin
Glenn Research Center, Cleveland, Ohio

Bei-Jiann Chang, Donald W. Johnson, and Christopher P. Garcia
QSS Group, Inc., Cleveland, Ohio

Prepared for the
2004 Fuel Cell Seminar
cosponsored by Air Products, Columbian Chemicals Company, CSA International,
PolyFuel, Inc., Porvair Fuel Cell Technology, Sud-Chemie, Tanaka Precious Metals, Toyota,
Umicore Autocat USA, Inc., U.S. Fuel Cell Council, and Yokogawa Corporation of America
San Antonio, Texas, November 1–5, 2004

National Aeronautics and
Space Administration

Glenn Research Center

January 2005
This report contains preliminary findings, subject to revision as analysis proceeds.

This work was sponsored by the Low Emissions Alternative Power Project of the Vehicle Systems Program at the NASA Glenn Research Center.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov
Hydrogen-Oxygen PEM Regenerative Fuel Cell Energy Storage System

David J. Bents and Vincent J. Scullin
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Bei-Jiann Chang, Donald W. Johnson, and Christopher P. Garcia
QSS Group, Inc.
Cleveland, Ohio 44135

Summary

An introduction to the closed cycle hydrogen-oxygen polymer electrolyte membrane (PEM) regenerative fuel cell (RFC), recently constructed at NASA Glenn Research Center, is presented. Illustrated with explanatory graphics and figures, this report outlines the engineering motivations for the RFC as a solar energy storage device, the system requirements, layout and hardware detail of the RFC unit at NASA Glenn, the construction history, and test experience accumulated to date with this unit.

Introduction

The PEM hydrogen-oxygen regenerative fuel cell system is potentially the highest storage capacity and lowest weight non-nuclear energy storage system for extra-terrestrial applications. A solar array equipped unmanned aerial vehicle (UAV) with a regenerative fuel cell energy storage system, for example, could provide a high altitude platform with theoretically unlimited endurance. This potential led NASA to undertake the practical development of a hydrogen-oxygen regenerative fuel cell, initially as solar energy storage for a high altitude, UAV science platform. At present, the RFC system is programmatically part of the NASA Vehicle Systems Program’s Low Emissions Alternative Power (LEAP) Project to further the development of aerospace regenerative fuel cells for high altitude and space missions.

The RFC system was designed to be a completely closed loop test bed for the cyclic operation of fuel cell systems up to 60 kWh (5 kWe X 12 hr). Closed loop means the system with its electrochemical reactants and products is completely sealed; nothing goes into the system other than electrical power and there are no discharges or emissions from the system other than electrical power and waste heat.

The RFC system can accommodate a fuel cell stack up to 5.25 kW (100 A at 52.5 V) capacity. The system has a maximum operating pressure of 400 psig. The electrolyzer operates at the system pressure while the fuel cell reactant feeds are regulated down to 50 psig. A 15 kW (150 A at 100 V) electrolyzer is used to charge the reactant tanks to full pressure while running under a current profile that simulates the output of a solar array during the 12-hr daylight cycle. During the nighttime phase of the solar cycle, the fuel cell runs at constant power for most of the cycle.

A DC power supply simulates the solar input to the electrolyzer and a DC load is used to sink the fuel cell current. The closed loop water supply provides source and cooling water for the electrolyzer, and humidification and discharge collection for the fuel cell.

Data acquisition and control for the RFC is provided by a multithreading suite of NASA Glenn developed software using the National Instruments LabVIEW™ programming language. The safety of
the test facility and hardware is enhanced by an automatic transfer of authority algorithm among the three PCs which are present on the RFC local area network.

Construction of the closed loop system began in 2002 at the NASA Glenn Research Center in Cleveland, Ohio, under the Environmental Research Aircraft and Sensor Technology (ERAST) project. System checkout was completed, and testing began, in July 2003 (ref. 1). The initial test sequences were done with only a fuel cell or electrolyzer in the test rig. Those tests were used to verify the test apparatus, procedures, and software. The first complete cycles of the fully closed loop, regenerative fuel cell system were successfully completed in the following September. Following some hardware upgrades to increase reactant recirculation flow, the test rig was operated at full power in December 2003, and again in January 2004. In March 2004, a newer generation of fuel cell and electrolyzer stacks was substituted for the original hardware and these stacks were successfully tested at full power under cyclic operation in June 2004.

Test experience so far has been limited by the number of multi-kilowatt rated hydrogen-oxygen fuel cell and electrolyzer stacks available, but initial results from these stacks are encouraging. To the best of our knowledge, this test facility is currently the only fully closed loop test facility in the United States for regenerative PEM hydrogen-oxygen fuel cell systems.

Closed loop testing presents both challenges and opportunities which are not present in open loop fuel cell testing. For example, the presence of inert gases in the reactant streams can noticeably degrade the fuel cell performance because the inerts are recycled. Inerts can enter the system whenever it is opened for installation or maintenance, or when commercial bottled gases are used to initially charge the reactant tanks. We have gotten around the problem of inert gas contamination from air/purge gas or commercial gas impurities by venting small amounts of gas from the fuel cell reactant recirculation loops during the first fuel cell cycle. Once the inert gases have been vented, successive cycles can be run with the system fully closed.

Similarly, contamination of the water resources by either mineral leaching or biological growth can degrade performance over time. In addition to a conductivity monitor, the system water loop is equipped with a de-ionizing resin bed, UV lamp and filter train to remove stray contaminants and bacteria. Nevertheless there is still some potential for buildup in other system reservoirs (for example the phase separator tanks). Possible contamination of the water resources from mineral leaching and biological growth is being monitored via chemical analysis of periodic system water samples.

Recombination of the reactant species inside the electrolyzer during shutdown periods has also proven to be a problem. With the source current removed from the electrolyzer, this recombination can cause a large differential pressure across the electrolyzer membranes because, on a per volume basis, the hydrogen is consumed twice as fast as the oxygen. We have implemented a trickle current loop to supply short bursts of low current to the electrolyzer to keep the pressure balanced during this recombination phase.

Finally, we have implemented a comprehensive water management scheme towards the goal of preserving reactant supply, since the reactant loss rate ultimately determines system service interval and lifetime. A set of electronic scales underneath the phase separator tanks allow us to keep a running inventory of the water supply, and a management routine in the control software keeps the operators apprised of the loss rate.

To date we have successfully met the challenges arisen from closed loop operation over successive charge/discharge cycles to 5 kWe power level and 12 hr run time. We anticipate further challenges to arise as we transition from multiple back-to-back test runs to multi-day and longer term continuous operations, in our quest to reduce to practice the operation of this RFC system as an energy storage device.
Reference


Figure 1.—Building 135 Regenerative fuel cell test site.
Figure 2.—Integrated equipment assembly inside Building 135 enclosure.
Figure 3.—Integrated equipment assembly: fuel cell and electrolyser stacks.
Figure 4.—Control room.
Figure 5.—RFC LabView control screen and process display.
Figure 6.—The gang that built the regenerative fuel cell.
Figure 7.—Electrolyzer stack.

Figure 8.—Fuel cell stack.
Figure 10.—Regenerative fuel cell test rig process block diagram.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL 111</td>
<td>Thermocouple, Type T</td>
<td>FH 201</td>
<td>Valve, Ball, Pneumatic</td>
</tr>
<tr>
<td>CL 113</td>
<td>Flow Meter, Turbine</td>
<td>FH 202</td>
<td>Pressure Regulator</td>
</tr>
<tr>
<td>CL 115</td>
<td>Thermocouple, Type T</td>
<td>FH 203</td>
<td>Scale</td>
</tr>
<tr>
<td>CL 144</td>
<td>Pump, Cooling</td>
<td>FH 240</td>
<td>Phase Separator, Hydrogen</td>
</tr>
<tr>
<td>CL 144</td>
<td>Pump, Water</td>
<td>HX 101</td>
<td>Heat Exchanger, Shell and Tube</td>
</tr>
<tr>
<td>DI 102</td>
<td>Thermocouple, Type T</td>
<td>HX 102</td>
<td>Heat Exchanger, Shell and Tube</td>
</tr>
<tr>
<td>DI 110</td>
<td>Flow Meter, Turbine</td>
<td>WB 107</td>
<td>Dryer, First</td>
</tr>
<tr>
<td>DI 150</td>
<td>Pump, Transfer</td>
<td>WB 108</td>
<td>Dryer, First</td>
</tr>
<tr>
<td>DI 154</td>
<td>Pump, Cooling</td>
<td>WB 109</td>
<td>Dryer, Second</td>
</tr>
<tr>
<td>DI 201</td>
<td>Valve, Ball, Pneumatic</td>
<td>WB 110</td>
<td>Dryer, Second</td>
</tr>
<tr>
<td>DI 202</td>
<td>Valve, Ball, Pneumatic</td>
<td>XO 103</td>
<td>Scale</td>
</tr>
<tr>
<td>EZ 1 - 60</td>
<td>Electrolyzer Cell Voltage tabs</td>
<td>XO 104</td>
<td>Flow Meter, Laminar</td>
</tr>
<tr>
<td>EZ 101</td>
<td>Electrolyzer Stack Current shunt</td>
<td>XO 105</td>
<td>Pump, Recirculation</td>
</tr>
<tr>
<td>EZ 102</td>
<td>Electrolyzer Stack Voltage</td>
<td>XO 113</td>
<td>Storage Tank, ASME Pressure Vessel</td>
</tr>
<tr>
<td>FC 1 - 64</td>
<td>Fuel Cell Cell Voltage tabs</td>
<td>XO 114</td>
<td>Contaminant Sensor</td>
</tr>
<tr>
<td>FC 101</td>
<td>Fuel Cell Stack Current shunt</td>
<td>XO 121</td>
<td>Sensor, Level</td>
</tr>
<tr>
<td>FC 102</td>
<td>Fuel Cell Stack Voltage</td>
<td>XO 139</td>
<td>Pressure Regulator, Back</td>
</tr>
<tr>
<td>FH 104</td>
<td>Flow Meter, Laminar</td>
<td>XO 140</td>
<td>Phase Separator, Oxygen</td>
</tr>
<tr>
<td>FH 105</td>
<td>Pump, Recirculation</td>
<td>XO 142</td>
<td>Thermocouple, Type T</td>
</tr>
<tr>
<td>FH 113</td>
<td>Storage Tank, ASME Pressure Vessel</td>
<td>XO 201</td>
<td>Valve, Ball, Pneumatic</td>
</tr>
<tr>
<td>FH 114</td>
<td>Contaminant Sensor</td>
<td>XO 202</td>
<td>Pressure Regulator</td>
</tr>
<tr>
<td>FH 139</td>
<td>Pressure Regulator, Back</td>
<td>XO 203</td>
<td>Scale</td>
</tr>
<tr>
<td>FH 140</td>
<td>Phase Separator, Hydrogen</td>
<td>XO 240</td>
<td>Phase Separator, Oxygen</td>
</tr>
<tr>
<td>FH 201</td>
<td>Valve, Ball, Pneumatic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 11.—Regenerative fuel cell—ingredients per schematic.
Figure 12.—Solar electric aircraft.
Figure 13.—Solar plane power train.
1) Energy capacity of fuel cell = Energy required to fly through night + Energy to run payload during night

2) Energy collected by solar array = Energy required to fly through day + Energy required to recharge fuel cells + Energy to run payload during day

Power for flight $W/m^2$

Time, hours from midnight

Figure 14.—Energy balance for continuous flight.

Figure 15.—Solar power available versus earth latitude from January to May.
Figure 16.—Energy storage requirements for 30-day continuous flight beginning June 7.

Figure 17.—Energy storage requirements for year-long continuous flight.
Why we are doing it?

- Key technology that enables future NASA missions
  - Solar energy storage of choice for day/night cycles > 4 hr
- Technical performance appears achievable
  - We can make it happen

Figure 18.—Why we are doing it?
Figure 19.—Voltage versus current 150 °F, 380 psig, April 29, 2004.

Figure 20.—Fuel cell voltage versus current, June 2, 2004.
Figure 21.—Solar day cycle.

Figure 22.—Solar night cycle.
Hydrogen-Oxygen PEM Regenerative Fuel Cell Energy Storage System

David J. Bents, Vincent J. Scullin, Bei-Jiann Chang, Donald W. Johnson, and Christopher P. Garcia

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191


An introduction to the closed cycle hydrogen-oxygen polymer electrolyte membrane (PEM) regenerative fuel cell (RFC), recently constructed at NASA Glenn Research Center, is presented. Illustrated with explanatory graphics and figures, this report outlines the engineering motivations for the RFC as a solar energy storage device, the system requirements, layout and hardware detail of the RFC unit at NASA Glenn, the construction history, and test experience accumulated to date with this unit.

Regenerative fuel cells; Energy storage

Unclassified - Unlimited
Subject Categories: 07 and 44

Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.