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Regenerative Fuel Cell Test Rig at Glenn Research Center

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

Ian J. Jakupca
Analex Corporation, Brook Park, Ohio

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

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REGENERATIVE FUEL CELL TEST RIG AT GLENN RESEARCH CENTER

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

Ian J. Jakupca
Analex Corporation
Brook Park, Ohio 44142

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

ABSTRACT

The regenerative fuel cell development effort at Glenn Research Center (GRC) involves the integration of a dedicated fuel cell and electrolyzer into an energy storage system test rig. The test rig consists of a fuel cell stack, an electrolysis stack, cooling pumps, a water transfer pump, gas recirculation pumps, phase separators, storage tanks for oxygen (O_2) and hydrogen (H_2), heat exchangers, isolation valves, pressure regulators, interconnecting tubing, nitrogen purge provisions, and instrumentation for control and monitoring purposes. The regenerative fuel cell (RFC) thus formed is a completely closed system which is capable of autonomous cyclic operation. The test rig provides direct current (DC) load and DC power supply to simulate power consumption and solar power input. In addition, chillers are used as the heat sink to dissipate the waste heat from the electrochemical stack operation. Various vents and nitrogen (N_2) sources are included in case inert purging is necessary to safe the RFC test rig.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
DC	Direct Current
ERAST	Environmental Research Aircraft and Sensor Technology
GRC	Glenn Research Center
IEA	Integrated Equipment Assembly
I/O	Input/Output
NASA	National Aeronautics and Space Administration
PC	Personal Computer
PEM	Proton Exchange Membrane
PID	Proportional Integral Derivative
RFC	Regenerative Fuel Cell
VI	Virtual Instrument

INTRODUCTION

The NASA GRC supports the development of an aerospace hydrogen-oxygen RFC under the Environmental Research Aircraft and Sensor Technology (ERAST) project of the Flight Research Base Program. The ERAST charter includes the development and demonstration of new technologies for unmanned aircraft that are suitable for earth science, including RFC equipped solar electric aircraft with potentially unlimited endurance. Although ERAST is an Aeronautics project, the RFC as a solar energy storage device is applicable to a wide variety of space and planetary surface missions as well as high altitude solar electric flight; hence, the widespread interest throughout NASA to bring this technology to a flight demonstration. Potentially the highest storage capacity and lowest weight of any non-nuclear device, an RFC aboard a solar electric aircraft flown continuously through several successive day-night cycles will provide the most convincing demonstration that this technology's widespread potential has been realized. Leading up to the flight demonstration are several laboratory and full scale demonstrations of key components and subsystems, including the coordinated operation of a hydrogen-oxygen fuel cell and electrolyzer unit as an energy storage system in a sealed, closed loop environment.

*Scientific Applications Development Branch
†Thermo-Mechanical Systems Branch

BACKGROUND

A test stand for evaluating Proton Exchange Membrane (PEM) electrolyzers has been in operation at GRC since January 2000. The stacks tested there include 4-cell, 8-cell short stacks, and full size prototype stacks that consumed 15 kWe power to generate O_2 and H_2 at pressures up to 400 psig. A test stand for characterizing PEM fuel cells was also constructed at GRC, and has been in operation since September 2000. The stacks that were tested on this stand include 4-, 8-, and 10 cell short stacks, and full size prototype stacks that produced up to 5.25 kWe from O_2 and H_2 reactant gasses at pressures up to 400 psig.

Both test stands ran on a once-through basis, i.e., no recycling of O_2, H_2, and water. The next step in the GRC test program was to combine the fuel cell and electrolyzer to form a closed loop RFC as an energy storage system based on the experiences gained in operating the two stand-alone test stands. The specific objectives of the RFC test rig were to simulate diurnal charge/discharge cycles, to observe long term performance of RFC, and to identify any degradation mechanisms.

The RFC design ground rules shown in Table 1 were set forth in the beginning of the test rig development. The RFC design specifications were based on solar airplane energy storage requirements and electrochemical stack availabilities. Interface requirements shown in Table 2 defined electrical and fluidic connections between the RFC and the test support equipment. A process block diagram for the regenerative fuel cell test rig was developed as in Figure 1.

TABLE 1.—DESIGN GROUNDRULES FOR REGENERATIVE FUEL CELL TEST RIG

1. Use commercial off-the-shelf and fabricated components to build a working rig initially.
2. Provide flexibility to incorporate flight-like components later.
3. Include additional sensors for data collection.
4. Provide O_2 and H_2 venting capabilities.
5. Provide N_2 purging and vacuum charging as service interfaces, not part of the rig.
6. Provide capability for collecting gas and water grab samples.

TABLE 2.—REGENERATIVE FUEL CELL INTERFACE REQUIREMENTS

Input Power: 0 to15 kW (150A@100.0V)
Output Power: 0 to 5.25 kW (100A@52.5V)
Maximum Heat Rejection: 4.48 kW (15,290 BTU/HR)
Maximum Inlet Coolant Temperature to Heat Exchanger: 50 °C
Maximum Exit Coolant Temperature from Heat Exchanger: 54 °C
Minimum Inlet Coolant Temperature to 1st Dryer: 0 °C
Maximum Exit Coolant Temperature from 1st Dryer: 5 °C
Minimum Inlet Coolant Temperature to 2nd Dryer: –40 °C
Maximum Exit Coolant Temperature from 2nd Dryer: –30 °C
Dimensions: 4 ft*6.5 ft*8 ft (Excluding O_2 and H_2 Storage Tanks)

The following sections describe the mechanical/electrochemical design, operational concepts, operating modes, control definitions, control/monitor instrumentation, primary control and LabVIEW controller as well as test support equipment.

MECHANICAL/ELECTROCHEMICAL DESIGN

A mechanical schematic was developed based on the RFC design requirements and specifications. One important design issue had to be resolved before the RFC system design could be finalized; the operating pressure of the fuel cell stack. Because of the difficulties the stack developers experienced in sealing the fuel cell stack at high pressures, pressure regulators were incorporated to allow low-pressure (50-psig) fuel cell operations. A water transfer pump was added to deliver water produced from the fuel cell to the eletrolyzer. Dedicated phase separator tanks were also added. The mechanical schematic reflecting these design decisions was prepared as shown in Figure 2, which details the process block diagram shown in Figure 1 into the following three interconnected process sections: 2(a) Fuel Cell; 2(b) Electrolyzer; 2(c) Reactant Storage Tanks and Driers. The major components list of the RFC is contained in Table 3 that includes the schematic symbol and description of each major component.

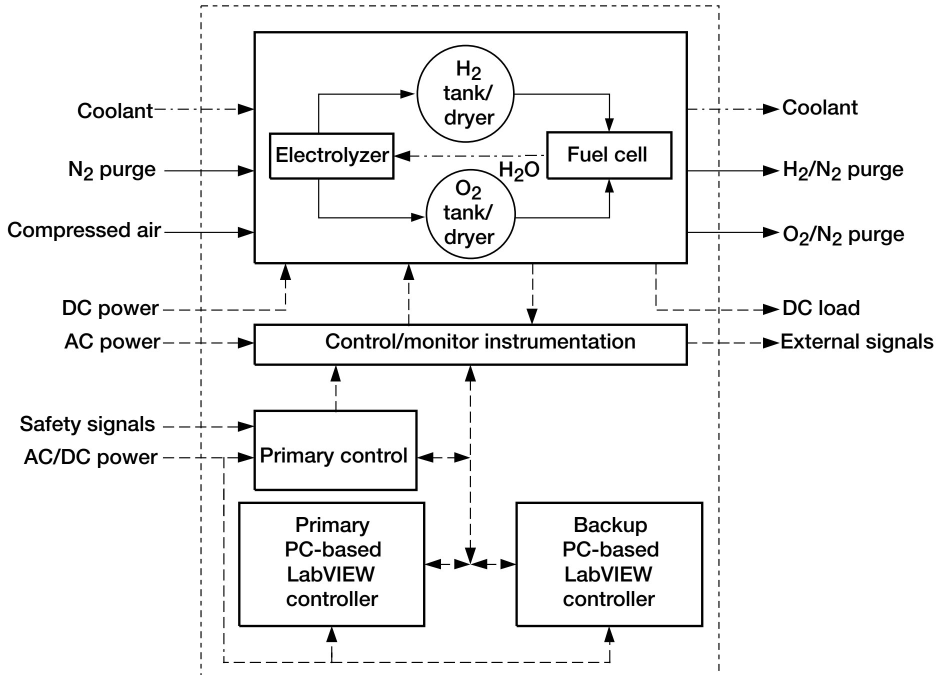

Figure 1.—Regenerative fuel cell test rig process block diagram.

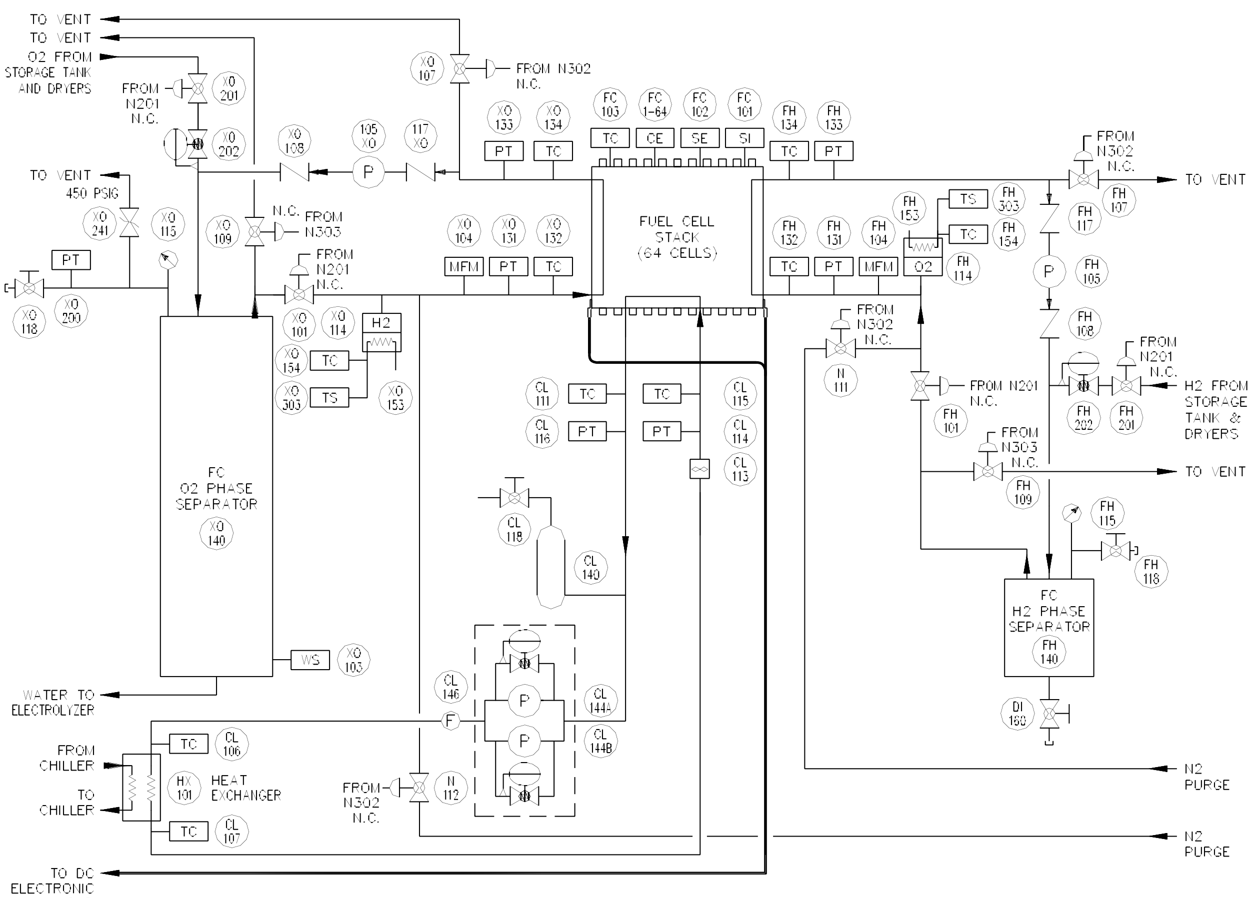

Figure 2a.—Fuel cell.

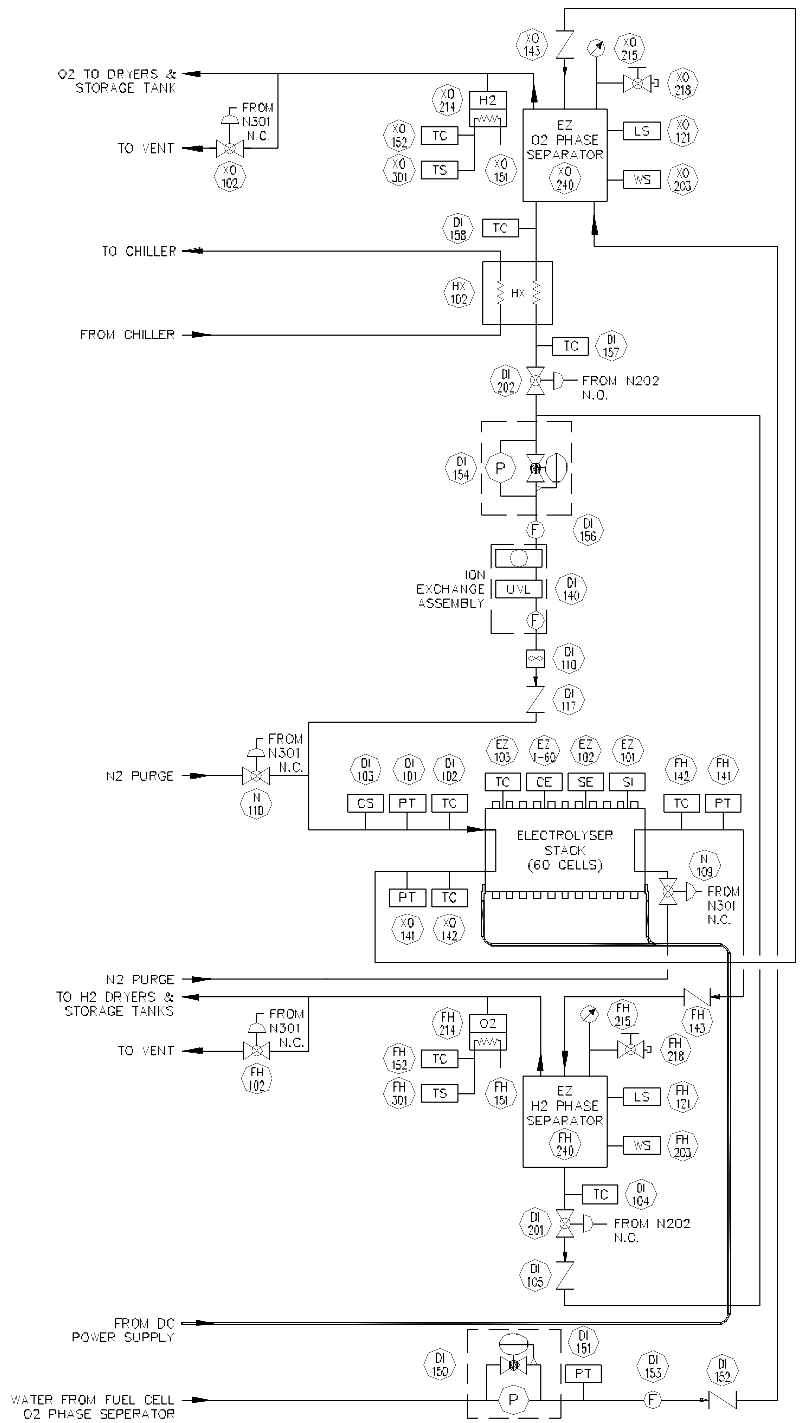

Figure 2b.—Electrolyzer.

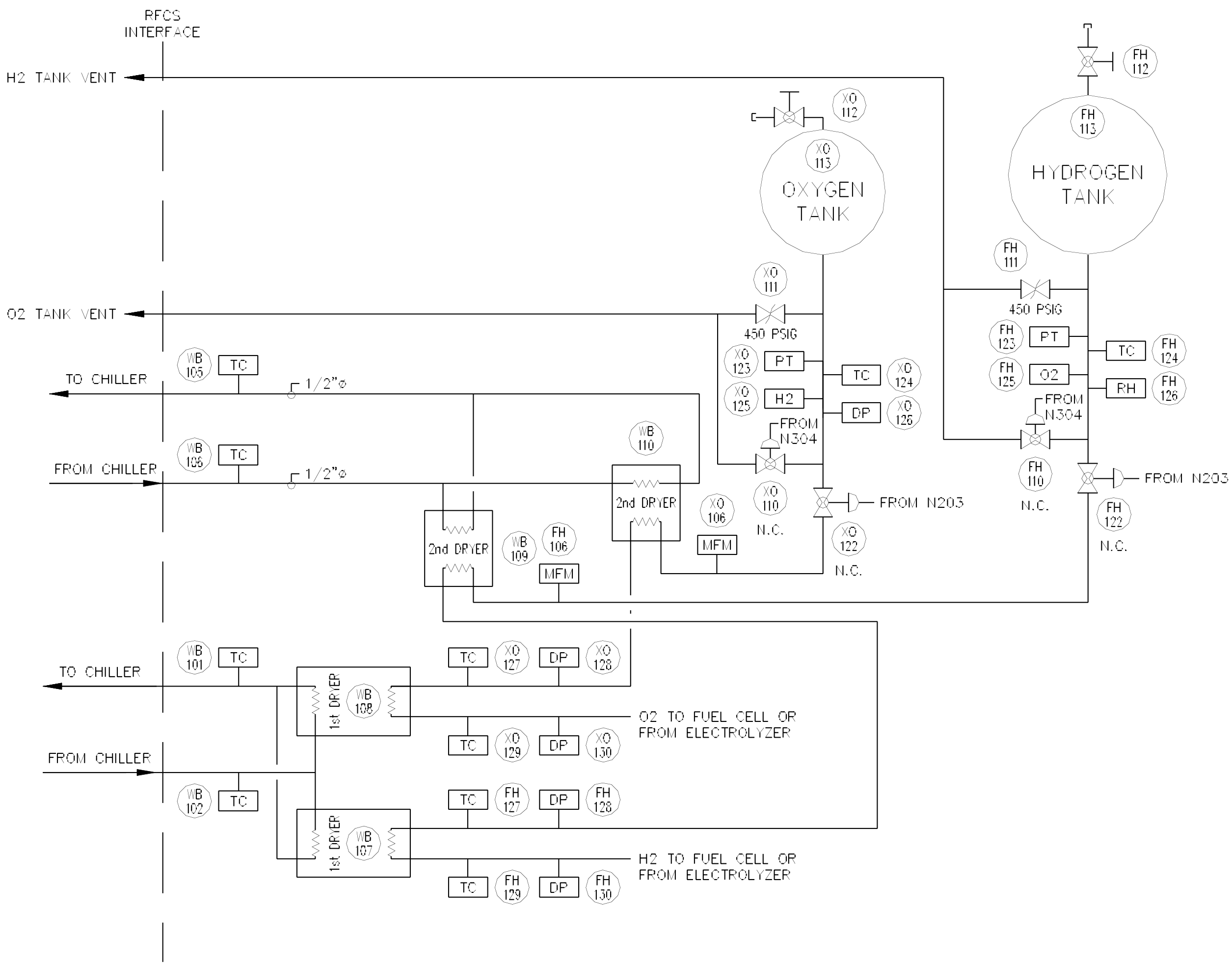

Figure 2c.—Reactant storage tanks and dryers.

TABLE 3.—RFC COMPONENT LIST

Schematic Symbol	Description
CL 111	Thermocouple, Type T
CL 113	Flow Meter, Turbine
CL 115	Thermocouple, Type T
CL 144	Pump, Cooling
DI 102	Thermocouple, Type T
DI 110	Flow Meter, Turbine
DI 150	Pump, Transfer
DI 154	Pump, Cooling
DI 201	Valve, Ball, Pneumatic
DI 202	Valve, Ball, Pneumatic
EZ 1 – 60	Electrolyzer Cell Voltage tabs
EZ 101	Electrolyzer Stack Current shunt
EZ 102	Electrolyzer Stack Voltage
FC 1 – 64	Fuel Cell Cell Voltage tabs
FC 101	Fuel Cell Stack Current shunt
FC 102	Fuel Cell Stack Voltage
FH 104	Flow Meter, Laminar
FH 105	Pump, Recirculation
FH 113	Storage Tank, ASME Pressure Vessel
FH 114	Contaminant Sensor
FH 139	Pressure Regulator, Back
FH 140	Phase Separator, Hydrogen
FH 201	Valve, Ball, Pneumatic
FH 202	Pressure Regulator
FH 203	Scale
FH 240	Phase Separator, Hydrogen
HX 101	Heat Exchanger, Shell and Tube
HX 102	Heat Exchanger, Shell and Tube
WB 107	Dryer, First
WB 108	Dryer, First
WB 109	Dryer, Second
WB 110	Dryer, Second
XO 103	Scale
XO 104	Flow Meter, Laminar
XO 105	Pump, Recirculation
XO 113	Storage Tank, ASME Pressure Vessel
XO 114	Contaminant Sensor
XO 121	Sensor, Level
XO 139	Pressure Regulator, Back
XO 140	Phase Separator, Oxygen
XO 142	Thermocouple, Type T
XO 201	Valve, Ball, Pneumatic
XO 202	Pressure Regulator
XO 203	Scale
XO 240	Phase Separator, Oxygen

All mechanical/electrochemical components and fluid interconnections are packaged within a frame to form the Integrated Equipment Assembly (IEA), except for the gas storage tanks and their associated sensors and valves. The IEA and an instrumentation cabinet are housed inside a shelter. The shelter is in turn located inside a building that serves as the safety barricade during RFC testing when people are not allowed in the test area. The tanks and associated hardware are sited outdoors on opposite sides of the building.

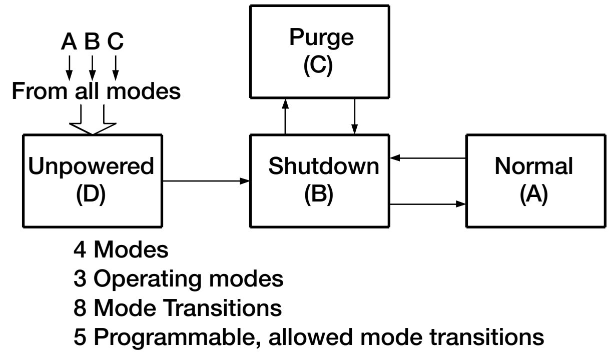

Figure 3.—RFC operating modes and allowable mode transitions.

If a fuel cell stack is capable of operating at pressures up to the electrolyzer's maximum pressure, the RFC schematic could be simplified by eliminating the additional cooling pump DI154, water transfer pump DI150, forward pressure regulators XO202 and FH202, as well as phase separators XO240 and FH240. The comparison of the high-pressure with the low- pressure fuel cell stacks in the RFC was discussed previously (Ref. 1). The current test rig may be converted to the "simplified" system at a later time when high-pressure fuel cell stacks become available.

OPERATIONAL CONCEPTS

During the period of time in which electrical energy is available to be stored, DC electrical power from the energy source (i.e., solar array) is applied to the electrolyzer stack. While the electrolyzer is generating the O_2 and H_2 product gases, the stack temperature is controlled by the water flow rate with waste heat rejected through heat exchanger HX102. Water consumed on the anode side causes the water level in O_2 phase separator XO240 to decrease and is replenished from the fuel cell O_2 phase separator XO140 via water transfer pump DI150. The water transported to the cathode side by association to migrating protons causes the water level of the H_2 phase separator FH240 to rise and is drained periodically by opening valve DI201 and closing valve DI202. Product gases O_2 and

H_2 flow through separators XO240 and FH240 to drop out bulk liquid water. The gases then pass through 1st dryers WB107 and WB108 to lower the dew point temperature to 40 °F followed by 2nd dryers WB109 and WB110 to further lower dew point temperature below –20 °F. The water condensed in the 1st dryers is drained back into the phase separators. The water vapor that has changed to ice is stored in the 2nd dryers to be thawed and returned to the fuel cell stack during the next cycle. The dried gases are delivered to reactant storage tanks XO113 and FH113 against rising pressures.

When the electrical energy source is no longer available (i.e., nightfall), or when the reactant storage tank has been filled to its 400 psig pressure limit, the DC power supplied to the electrolyzer is turned off. Valves XO201 and FH201 open to allow reactants O_2 and H_2 to flow into the fuel cell stack at a stepped down pressure of 50 psig via pressure regulators XO202 and FH202. The current draw from the fuel cell will ramp up to the full power of 5.25 kWe. Adjusting the pump CL144 motor speed that controls the coolant flow rate through the stack and heat exchanger HX101 maintains the fuel cell stack temperature. The reactants recirculate through the stack using pumps XO105 and FH105. A fixed stoichiometric ratio relative to the current draw is maintained by adjusting the pump speed in response to temperature or pressure changes. The O_2 recirculation also ensures the water produced on the cathode side is removed from the stack and stored in the O_2 phase separator XO140. The set point of chiller coolant for the 2nd dryer is raised to 68 °F to thaw the ice and humidify the reactants to the fuel cell. When sufficient daylight returns or the tank pressure drops below 50 psig, the RFC switches back to electrolyzer operation and starts another diurnal cycle.

Water quantities in the system are monitored by weight sensors on the phase separators which allow the operator to track reactant inventory. Contaminant sensors are placed in the O_2 and H_2 flow streams near the phase separators and storage tanks to detect the presence of combustible mixtures due to gas cross over in the electrochemical stacks. N_2 purge is available for the electrolyzer stack plus its phase separators, fuel cell stack, and fuel cell phase separators. The reactant storage tanks can be depressurized if necessary by venting to ambient.

OPERATING MODES

The RFC operates in one of following four modes: Unpowered, Shutdown, Normal, and Purge. Each mode produces different settings and control states in how the RFC is operated. Definitions for each of these operating modes is presented in Table 4. Figure 3 illustrates the RFC operating modes and allowable mode transitions. Details of the individual mode transitions are contained in the “RFC Day Cycle Program” control software presented in the “Primary control and LabVIEW Controller” discussion section of this paper.

TABLE 4.—RFC MODE DEFINITIONS

Mode	Definition
Shutdown	The electrolyzer is not generating H_2 and O_2 and the fuel cell is not generating power. Both stack currents are at zero and all actuators are deenergized. The system is powered and all sensors are working. The Shutdown mode is called for by: • Manual actuation • High FC stack temperature • High EZ stack temperature • Low FC cell voltage • High EZ cell voltage • Low EZ cell voltage • High FC O_2 outlet temperature • High FC H_2 outlet temperature • High EZ O_2 outlet temperature • High EZ H_2 outlet temperature • High FC cooling water outlet temperature • High EZ water conductivity • High O_2 concentration in H_2 phase separator • High H_2 concentration in O_2 phase separator • High O_2 concentration in H_2 storage tank • High H_2 concentration in O_2 storage tank • High EZ O_2 outlet pressure • High EZ H_2 outlet pressure • High FC O_2 inlet pressure • High FC H_2 inlet pressure • High EZ H_2/O_2 pressure differential • Low EZ H_2/O_2 pressure differential • High FC H_2/O_2 pressure differential • Low FC H_2/O_2 pressure differential • High FC O_2/water pressure differential • Low FC O_2/water pressure differential • Low water pump flow • High O_2 storage tank pressure • High H_2 storage tank pressure • High O_2 storage tank temperature • High H_2 storage tank temperature • Low O_2 phase separator level • Low H_2 phase separator level • High H_2 phase separator level • High facility H_2 concentration • High facility fire detection • FieldPoint watchdog timer failure

TABLE 4.—RFC MODE DEFINITIONS (Concluded)

Mode	Definition
Normal	The RFC is performing its function, either storing H_2 and O_2 with the electrolyzer operating according to the power profile or generating electrical power at 5.25 kWe with the fuel cell. The Normal mode is called for by: • Manual actuation
Purge	The RFC is being purged with N_2 or vented. There are four options available: purging electrolyzer stack, purging fuel cell stack, venting fuel cell phase separator tanks, or venting storage tanks. The Purge mode is called for by: • Manual actuation
Unpowered	No electrical power is applied to the RFC. The RFC is at the pressure and temperature when the power was lost. The Unpowered mode is called for by: • Manual actuation (turn switch) • Electrical power failure

CONTROL DEFINITIONS

The process controls for the RFC are listed in Table 5 along with the associated process parameters, actuators, sensors, set points, and ranges. The first six controls are set point changes based on given profiles or conditions. The recirculation flow rate controls and stack temperature controls are feed back controls that require proportional, integral and derivative (PID) control algorithms. Their block diagrams are shown in Figures 4 to 7.

CONTROL/MONITOR INSTRUMENTATION

National Instruments' FieldPoint™ input/output (I/O) modules are used to modularize the communication, I/O functions, and signal termination of the RFC sensors and actuators. These units are networked using one primary and two backup personal computers (PC's) to perform data acquisition and control functions using Ethernet bus topology. Use of Field Point via an ethernet bus was selected for this test rig due to the need to site the rig in an isolated location and operate it remotely (safety purposes) and the large number of instruments and actuators aboard, which would otherwise need >750 ft of hard wired connections for each instrument. A fiber optic cable and Ethernet multi-port managed switching hubs provide the link between the control room and the shelter location where the rig is sited. Most sensors and actuators in the rig are wired to the FieldPoint distributed modules except for those with RS232 and RS485 serial links that are directly connected to the switching hub at the rig. The data link block diagram is presented in Figure 8.

TABLE 5.—CONTROL DEFINITIONS FOR RFC

No.	Name	Actuator(s)	Sensor(s)	Setpoint(s)	Range(s)
1	Electrolyzer Current	Power Supply	EZ101	Variable per Profile	0 to 150 A
2	Fuel Cell Current	Electronic Load	FC101	100 A	0 to 100 A
3	H_2 and O_2 2nd Dryer High Temperature	Chiller	N/A	20 °C	0 to 25 °C
4	H_2 and O_2 2nd Dryer Low Temperature	Chiller	N/A	–40 °C	–40 to –30 °C
5	EZ H_2 Phase Separator Level	N_20_2 (DI201,DI202) Energized on high Deenergized on low	FH121	High: 18 in. Low: 8 in.	4 to 22 in.
6	EZ O_2 Phase Separator Level	DI150 Powered on low Unpowered on high	XO121	High: 18 in. Low: 8 in.	4 to 22 in.
7	H_2 Recirculation Flow Rate	FH105	FH104	58 slpm	0 to 60 slpm
8	O_2 Recirculation Flow Rate	XO105	XO104	45 slpm	0 to 60 slpm
9	Electrolyzer Temperature	DI154	XO142 XO142–DI102	158 °F 15 °F	68 to 178 °F 0 to 18 °F
10	Fuel Cell Temperature	CL144	CL111 CL111–CL115	158 °F 15 °F	68 to 178 °F 0 to 18 °F

Facility fire and H_2 detectors are placed around the test rig in accordance with the applicable safety standards (Ref. 2). A close circuit television is installed to provide the operator in the control room with audiovisual monitoring of the test rig site.

PRIMARY CONTROL AND LABVIEW CONTROLLER

The Primary Control relay logic circuit provides manual switching of power to RFC and emergency shutdown capabilities. The facility fire and H_2 sensors relay circuit also triggers emergency RFC shutdown if an alarm level is reached. Lights on the panel indicate the system power status. In addition, a reset button is provided to clear a latched emergency shutdown condition. All faults must be resolved to complete a system-reset operation. The block diagram for Primary Control is illustrated in Figure 9.

At the center of the PC-based LabVIEW controller is the RFC Day Cycle Program that consists of a

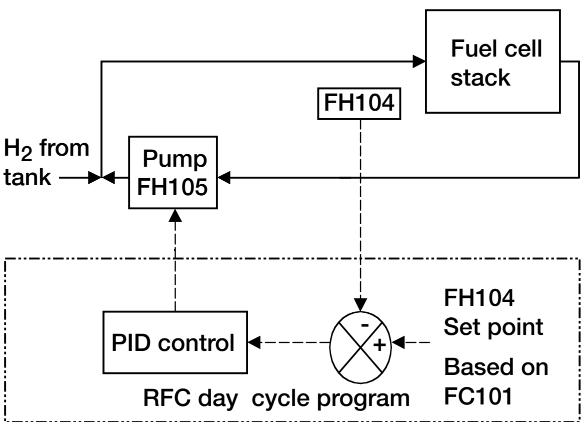

Figure 4.—H_2 recirculation flow rate control loop.

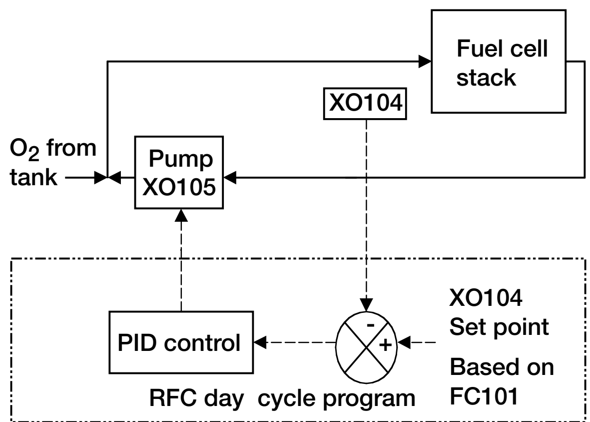

Figure 5.—O_2 recirculation flow rate control loop.

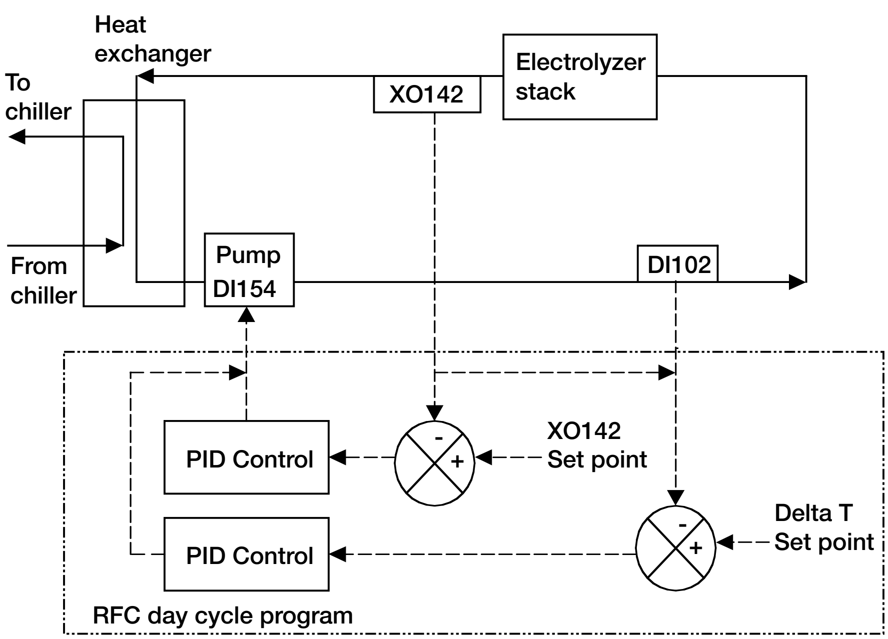

Figure 6.—Electrolyzer temperature control loop.

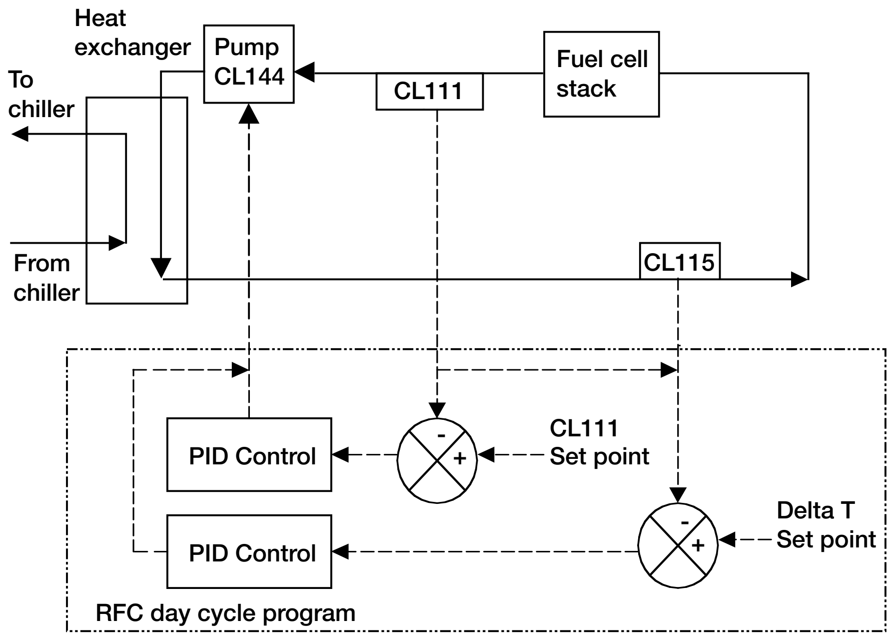

Figure 7.—Fuel cell temperature control loop.

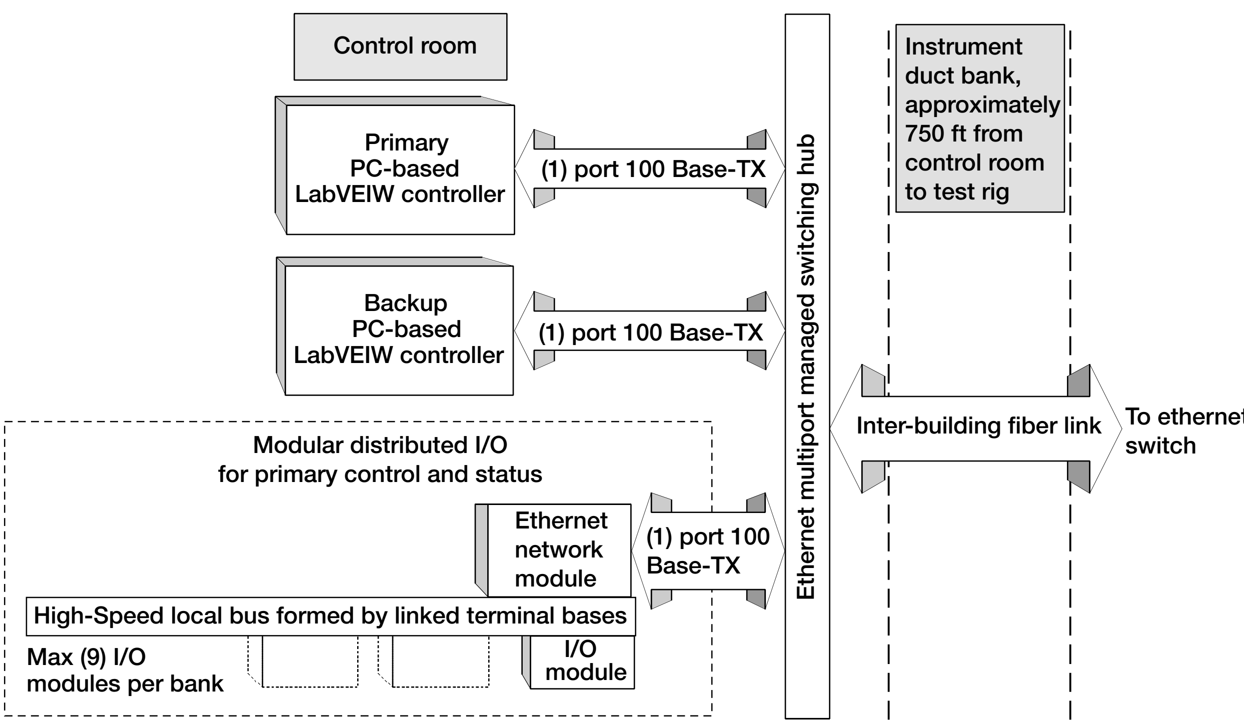

Figure 8a.—Regenerative fuel cell serial data signal topology.

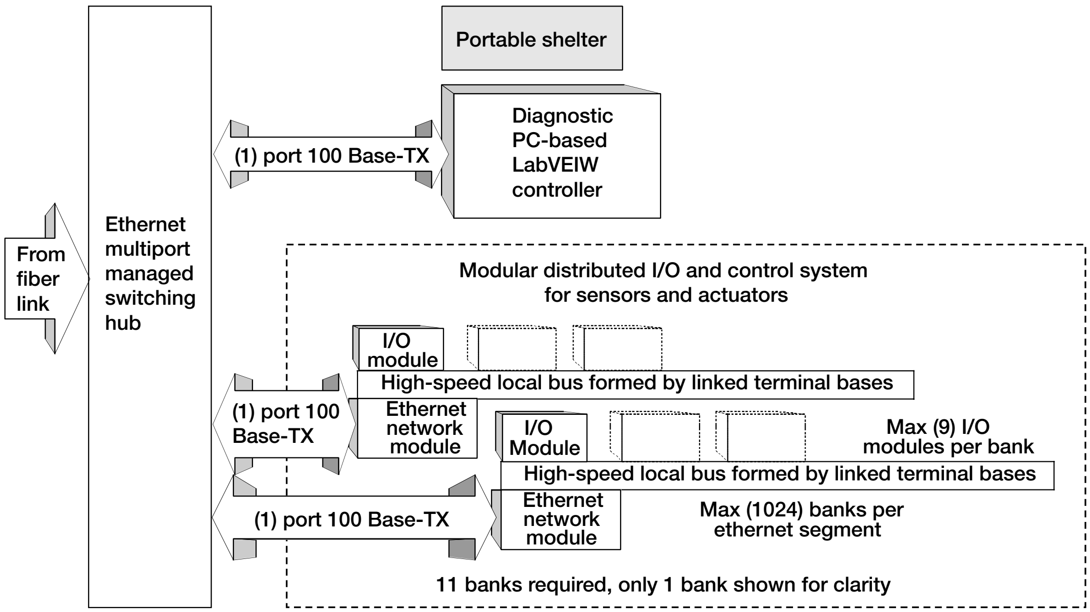

Figure 8b.—Regenerative fuel cell serial data signal topology.

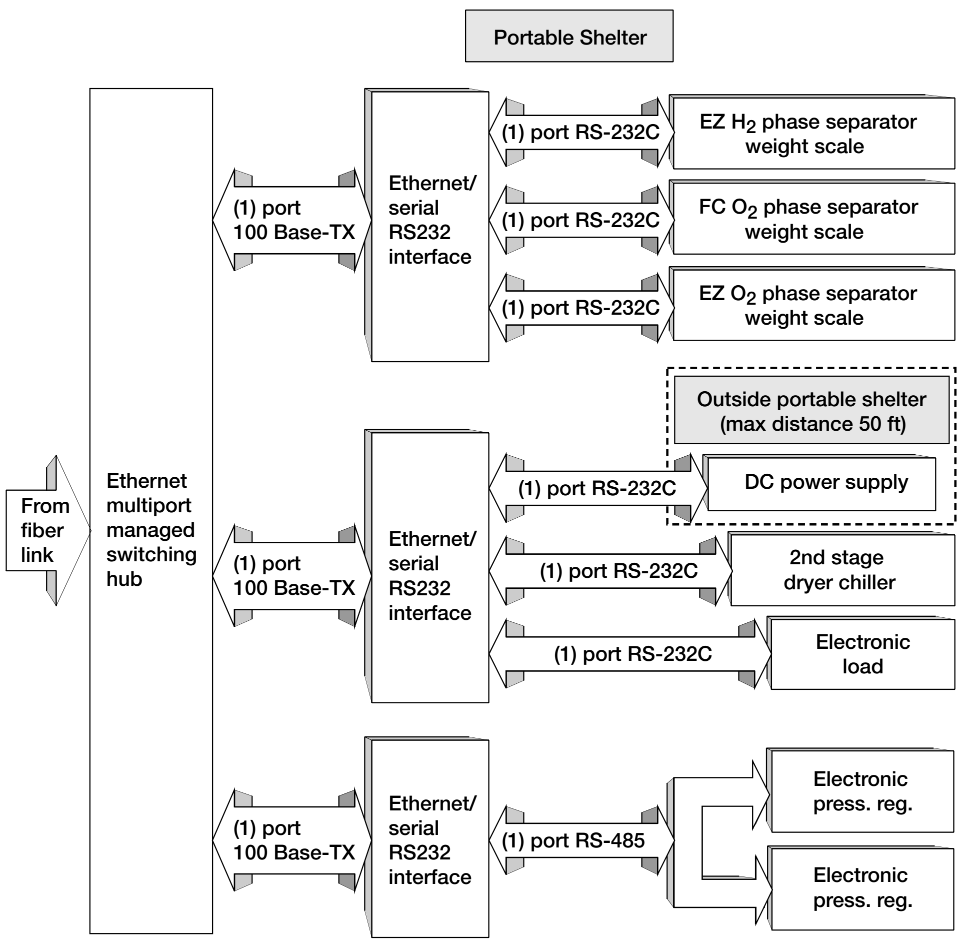

Figure 8c.—Regenerative fuel cell serial data signal topology.

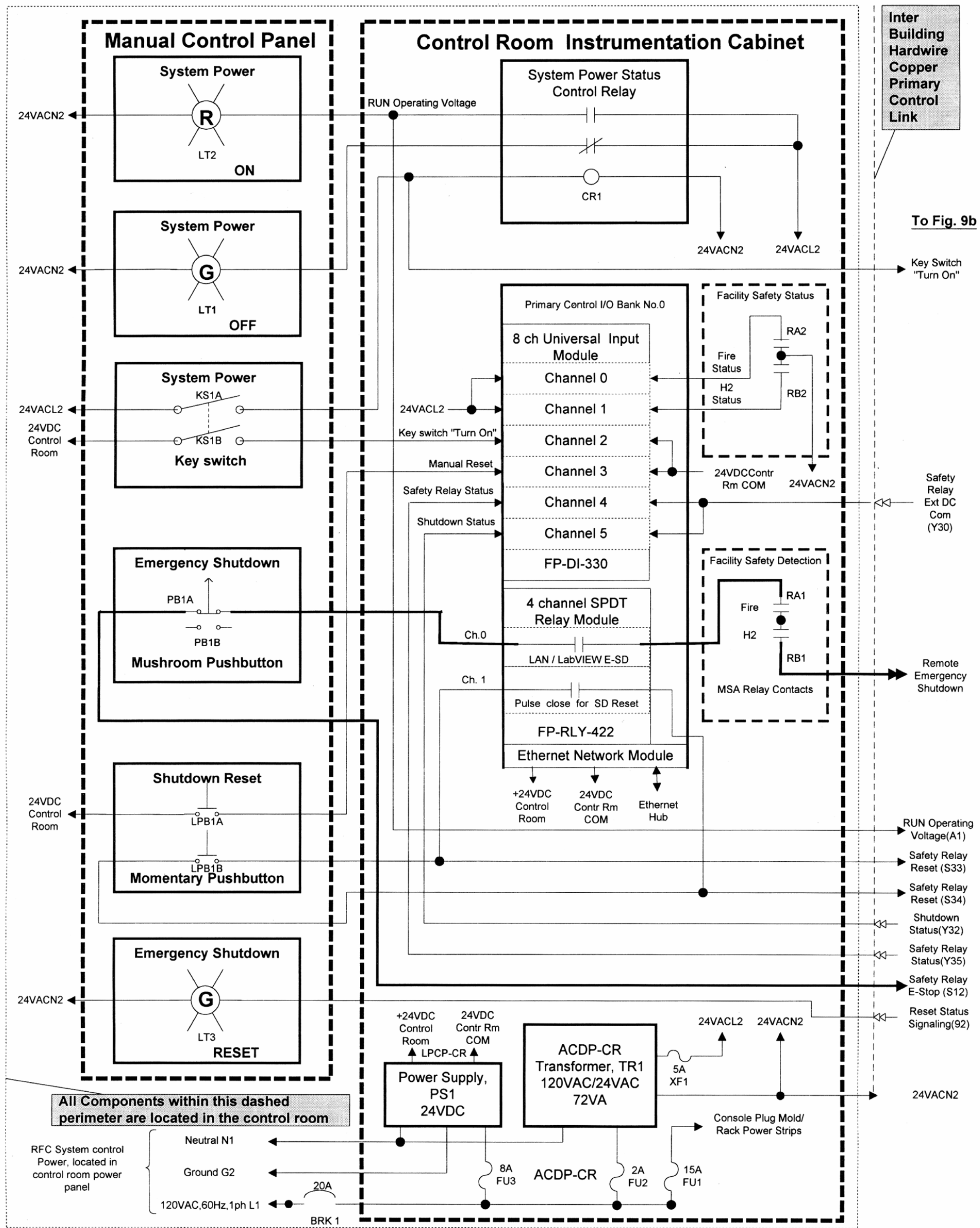

Figure 9a.—Regenerative fuel cell system primary control and facility safety emergency shutdown protection.

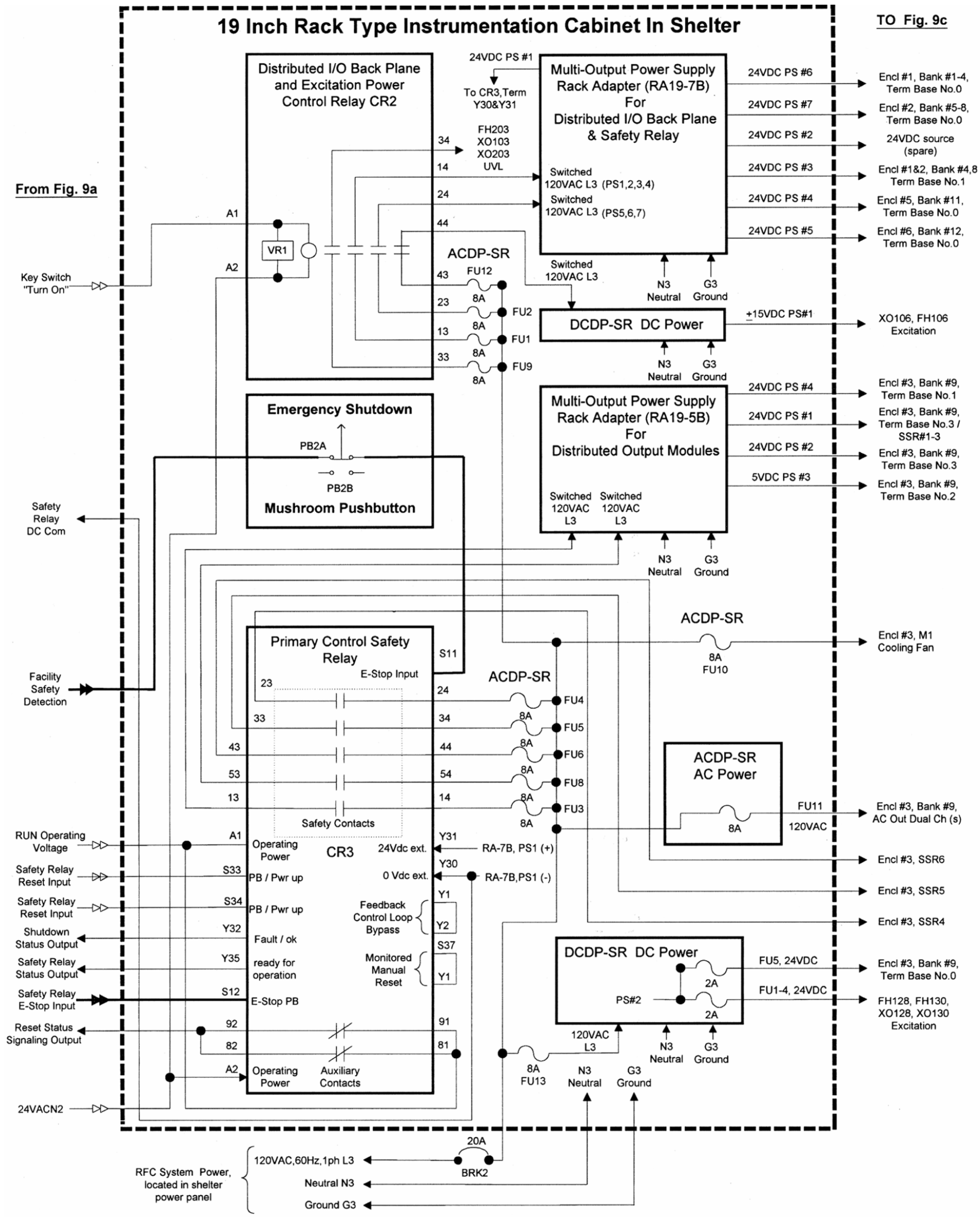

Figure 9b.—Regenerative fuel cell system primary control and facility safety emergency shutdown protection.

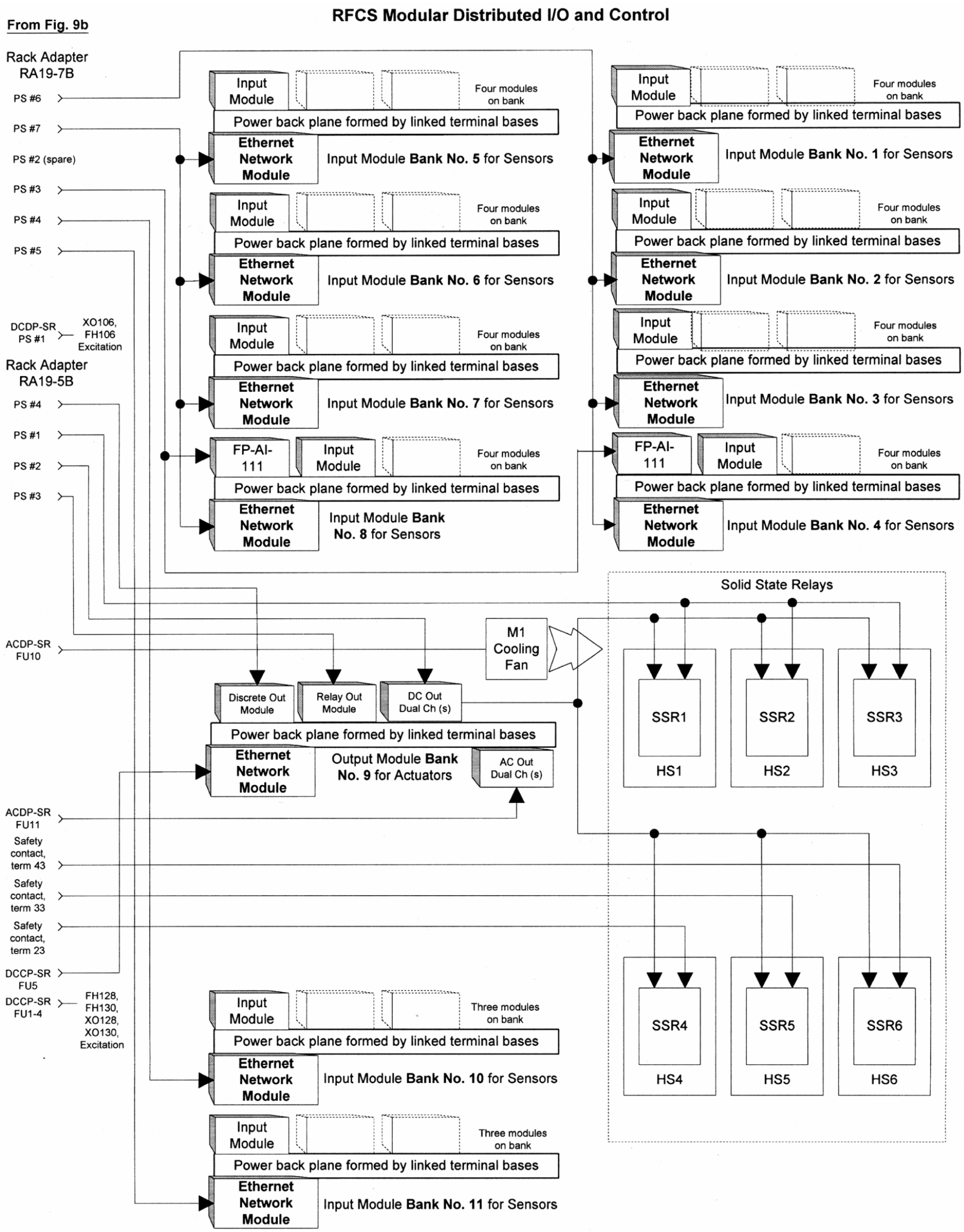

Figure 9c.—Regenerative fuel cell system primary control and facility safety emergency shutdown protection.

supervisory virtual instrument (VI) and multiple independent VIs called by the supervisory VI. The software program performs the following tasks: sequencing mode transition and cyclic operation, converting and displaying sensor readings in engineering units, running control algorithms, limit checking for warnings and alarms, writing data to files for future retrieval, and providing operator interfaces with the RFC.

The Day Cycle program is designed to run simultaneously on all three of the RFC computers under a master/slave paradigm. As each computer is brought on-line, it listens for a master "heartbeat" from the other PCs. If it does not hear the heartbeat, it starts itself up as the master and begins transmitting the master heartbeat. If it does hear the heartbeat on startup, it designates itself as a slave. The role of the master is to acquire all of the system data and publish that data to the slaves, as well as to operate all of the system controller software. The slave PCs can read the data from the master and display it, and observe, but not direct, all of the controller operations. The slave PCs also listen continuously for the master heartbeat. If that heartbeat should ever disappear, in evidence of a loss of power or functionality on the part of the existing master, then the slave PCs initiate an automatic transfer of authority to make one of them the new master. Which slave becomes the new master depends on: (a) which one first detects the master has dropped out, and (b) where its IP address appears on a predetermined hierarchy list (diagnostic PC comes last). Because the same Day Cycle program runs on all three PCs, any of the three can operate as the master and the RFC system can run with one, two, or all three of the PCs on-line. The primary "master" PC and one "slave" PC reside in the control room. The second "slave" PC resides at the remote site in an instrumentation cabinet next to the equipment, where it is also used for checkout and diagnostic purposes. The front panels of the main screen VI and the process display VI are shown in Figures 10 and 11, respectively.

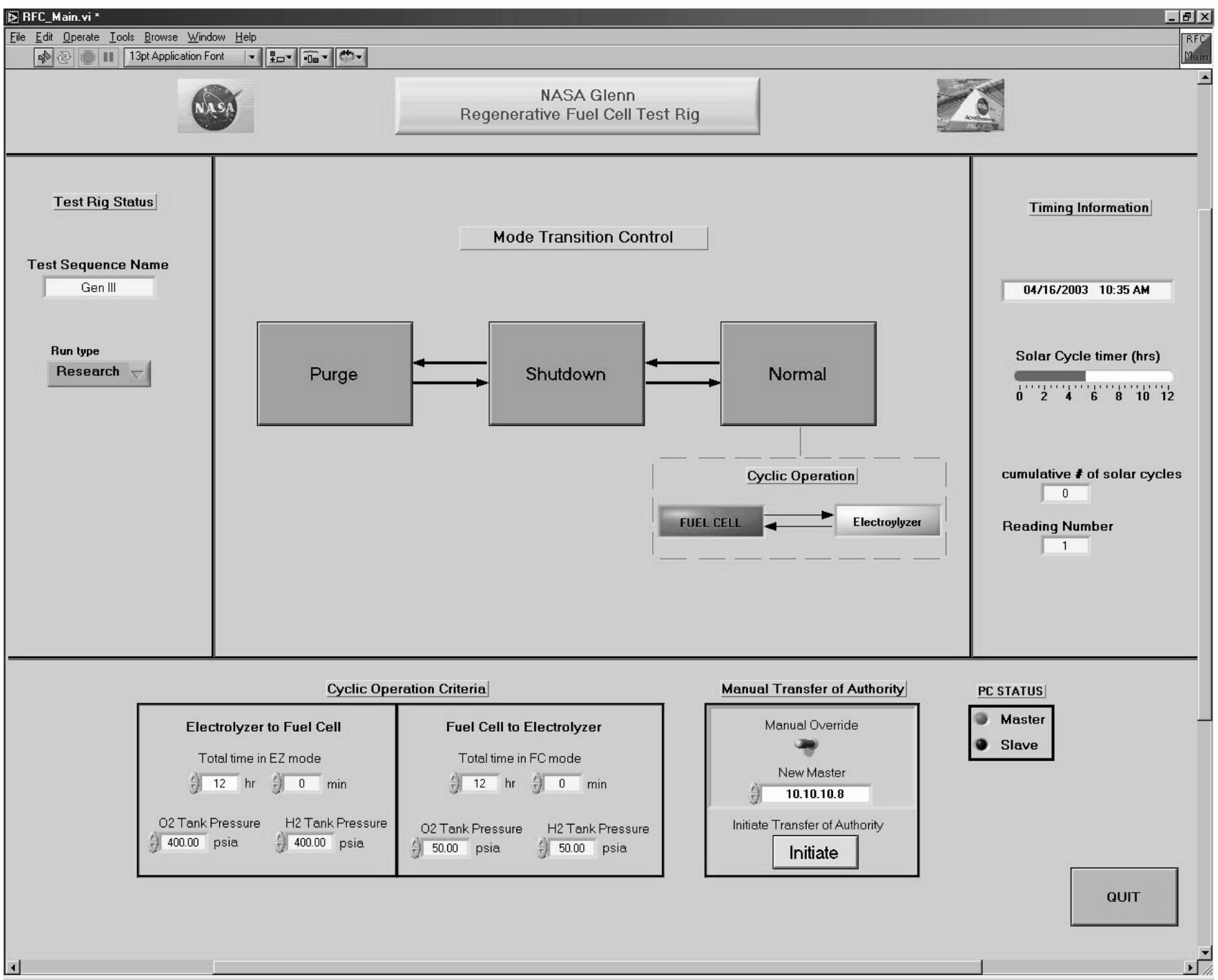

Figure 10.—Main screen VI.

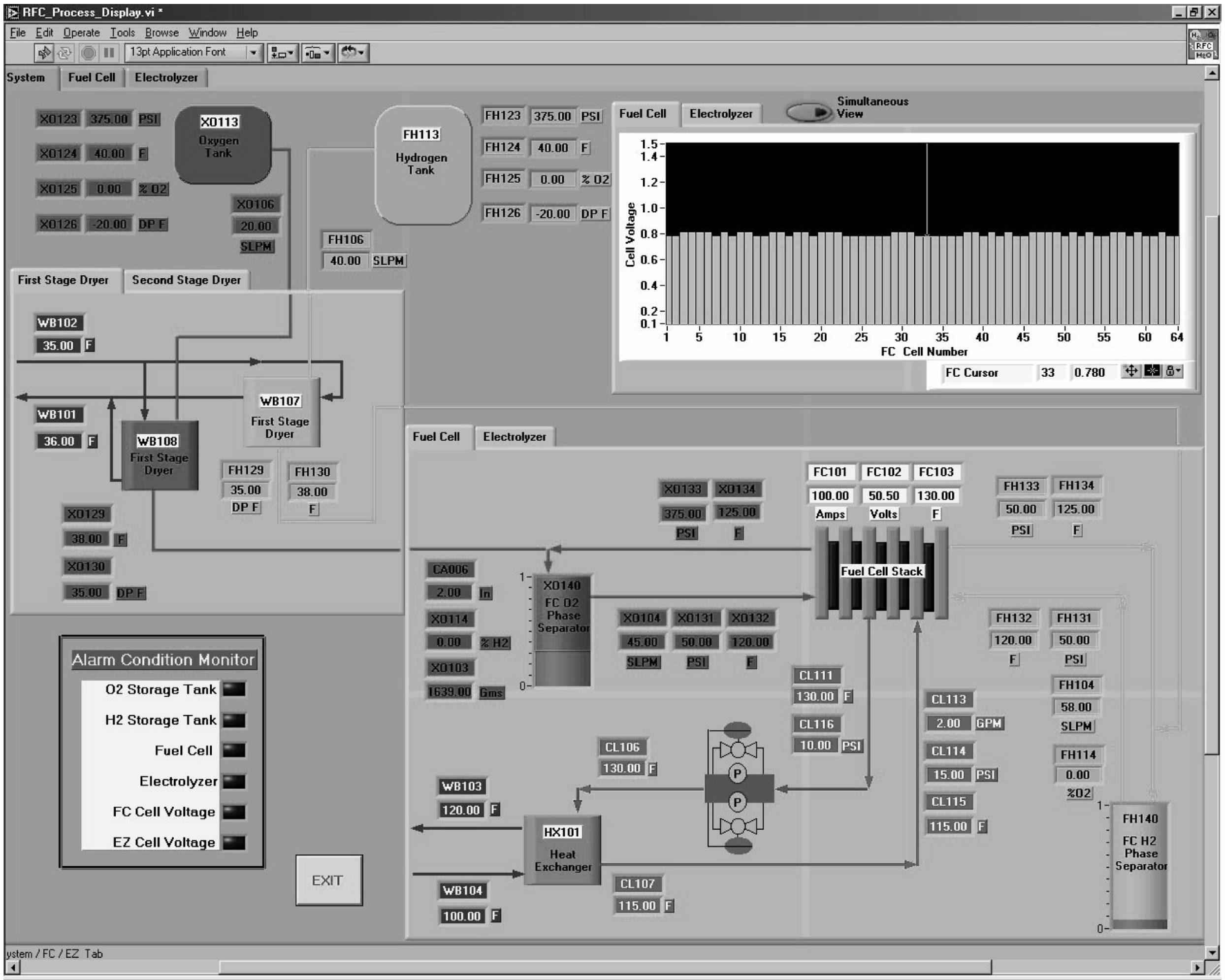

Figure 11.—RFC process display VI.

TEST SUPPORT EQUIPMENT

The test support equipment includes a DC power supply, a DC electronic load, a main chiller, a 1st dryer chiller, a 2nd dryer chiller, a vacuum pump, N_2 bottles and compressed air. They are commercially available hardware that provides the interfaces for the RFC testing. Table 6 summarizes the specifications of the test support equipment.

TABLE 6.—TEST SUPPORT EQUIPMENT

Item	Specification
DC Power Supply	200A @ 150V
DC Electronic Load	12 kWe with 1000A max.
Main Chiller	10 kWe @ 5 gpm
1st Dryer Chiller	200 W @ 1 °C
2nd Dryer Chiller	100 W @ –40 °C
Vacuum Pump	<80 mbar
N_2 K bottle	>450 psig
Compressed Air	80 to 120 psig

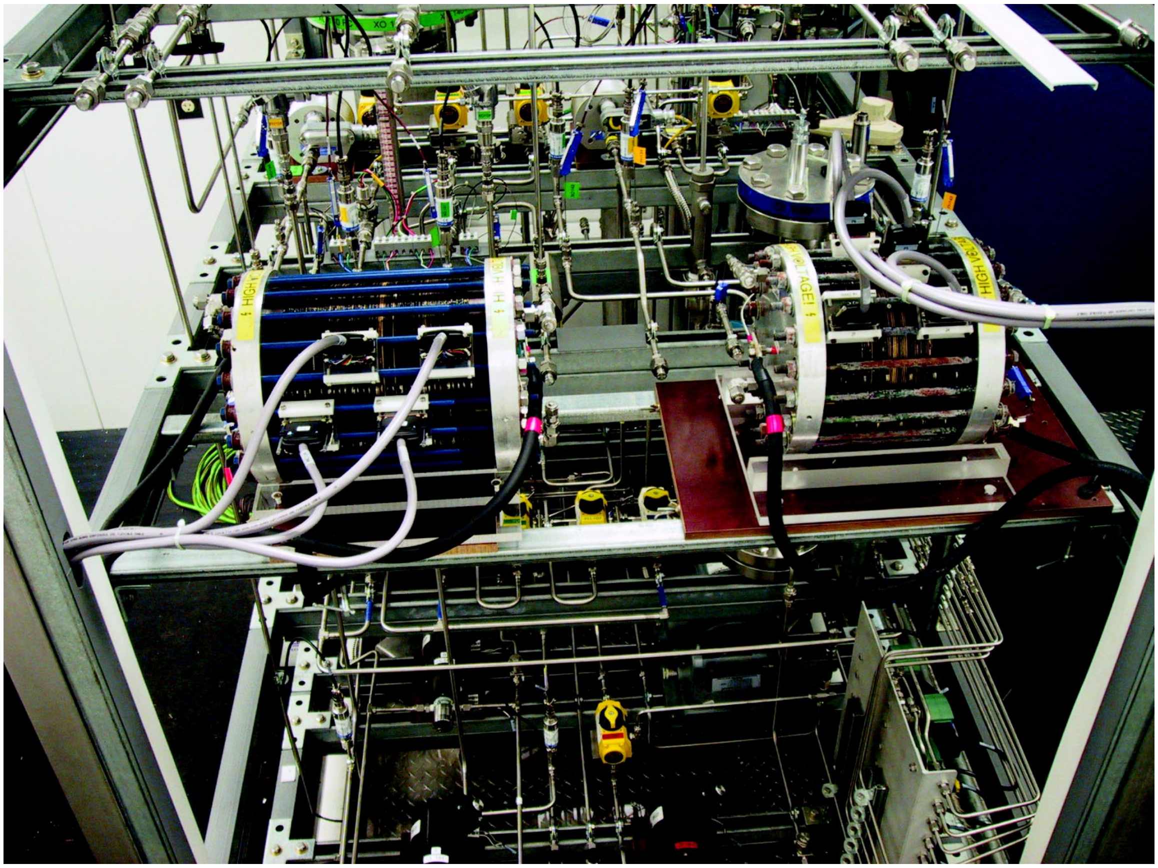

Figure 12.—Integrated equipment assembly.

CONCLUSIONS

This test rig was built up over calendar year 2002–03 and is presently undergoing mechanical, electrical and software checkout. Figure 12 is a photograph of the IEA with the fuel cell stack and electrolyzer stack shown in the foreground.

Checkout operations of individual process sections per Figures 2(a), 2(b), and 2(c) will commence as soon as the initial checkout is completed. The coordinated operation of fuel cell and electrolyzer subsystems as end-to-end energy storage system is scheduled to take place before the end of fiscal year 2003. Additional characterization tests and inclusion of latest generation of fuel cell and electrolyzer stacks are planned for the future.

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

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National Aeronautics and Space Administration
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13. ABSTRACT ***(Maximum 200 words)***

The regenerative fuel cell development effort at Glenn Research Center (GRC) involves the integration of a dedicated fuel cell and electrolyzer into an energy storage system test rig. The test rig consists of a fuel cell stack, an electrolysis stack, cooling pumps, a water transfer pump, gas recirculation pumps, phase separators, storage tanks for oxygen (O_2) and hydrogen (H_2), heat exchangers, isolation valves, pressure regulators, interconnecting tubing, nitrogen purge provisions, and instrumentation for control and monitoring purposes. The regenerative fuel cell (RFC) thus formed is a completely closed system which is capable of autonomous cyclic operation. The test rig provides direct current (DC) load and DC power supply to simulate power consumption and solar power input. In addition, chillers are used as the heat sink to dissipate the waste heat from the electrochemical stack operation. Various vents and nitrogen (N_2) sources are included in case inert purging is necessary to safe the RFC test rig.

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