INTERNAL VOLTAGE CONTROL OF HYDROGEN-OXYGEN FUEL CELLS - FEASIBILITY STUDY

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16. Abstract

An experimental study was conducted to assess the feasibility of internal voltage regulation of fuel cell systems. Two methods were tested. In one, reactant partial pressure was used as the voltage control parameter and in the other reactant total pressure was used for control. Both techniques were breadboarded and tested on a single alkaline-electrolyte fuel cell. Both methods were found to be possible forms of regulation, however, of the two the total pressure technique would be more efficient, simplier to apply and would provide better transient characteristics.

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FUEL CELLS - FEASIBILITY STUDY

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SUMMARY

An experimental study was conducted to explore the feasibility of internal or source voltage regulation of fuel cell systems. Two techniques were investigated. In one, a reactant was diluted with a controlled amount of inert gas to throttle the cell reaction and thereby gain control of the cell voltage. In the other method, the pressure of both reactants in the fuel cell was used as the voltage control parameter. Various voltage sensitivity and response characteristic data were taken for both methods and actual regulation systems were breadboarded and tested on a single alkaline-electrolyte fuel cell of the type being considered for use on the Space Shuttle. The data taken show both methods to be workable regulation techniques; however, the ambient or "total pressure" technique would be simpler to apply and would provide a faster response to voltage changes.

INTRODUCTION

In the development of space power fuel cell systems the voltage regulation requirement of the load has generally been ignored as a system design parameter. In general, the design philosophy has been to build a fuel cell system with generating capacity sufficient to maintain the load bus voltage within a specified range as the power demand varies between its nominal high and low limits. Any regulation that is required is typically done at the various load components or power distribution centers. On this basis, emphasis has been placed on developing and improving standard regulating devices with little or no effort directed toward exploring the possibility of direct or internal regulation of the fuel cell system itself.

The application of internal regulation could be advantageous from the standpoint of reducing the overall system weight through the elimination of the various electronic regulating devices. Also, the possibility of gaining continuous, compensating control of fuel

cell performance is an attractive feature that internal regulation would provide. Thus, the purpose of this study is to investigate the feasibility of internal or source voltage regulation of fuel cell systems. Using a single shuttle-type fuel cell as a test bed, two regulation techniques were investigated. In one method the oxygen partial pressure of an oxygen-inert gas mixture was used as the voltage control parameter and in the other the pressure of both reactants was used for control. It was felt that these two techniques provide the most promising methods of internal voltage control. In the "partial pressure" system the oxygen reactant was diluted with nitrogen in the proportion required to throttle the cell reaction and thus hold the cell voltage to the desired regulated value. To test this technique, an existing fuel cell dynamics test apparatus (ref. 1) was modified to enable an inert gas (N_2) to be mixed with the reactant oxygen of an operating cell. Various data were taken, these included reactant-dilution, voltage-sensitivity characteristics, and transient response characteristics. An actual "partial pressure" regulator was breadboarded and several load step response tests were run.

In the other method tested, the total pressure of both reactants was used as the voltage regulation parameter. A reactant pressure control loop having cell voltage as its control parameter was breadboarded on the dynamics rig and this concept was tested. As was done for the partial pressure method, basic voltage sensitivity and transient response data were taken and various closed-loop-regulation response tests were run.

This study was conducted on the premise that a source voltage regulation system would be designed to work only between the nominal high and low levels of the fuel cell design power range. It was assumed that if the system would be required to go below the normal low limit of the design power profile, an auxiliary system such as a parasitic load regulator would actuate to hold the voltage in regulation. Similarly, should the system be required to go above the nominal high power limit and into a high power density mode, a shaping regulator would function to hold the cell voltage within range.

APPARATUS

Test Rig

The fuel cell dynamics test apparatus was used to generate the humidified hydrogen stream required by the fuel cell. The apparatus provides automatic control of the stream parameters of temperature, pressure, flow rate, and humidity.

A block diagram flow schematic of the basic test loop is shown in figure 1. The rig is comprised of four closed-loop control systems. A hydrogen stream at a desired humidity is produced by mixing superheated steam and hydrogen. The desired mixture ratio or humidity is set up by controlling the flow rate of each component of the mixture. This is done by regulating the pressure upstream of sonic flow orifices in both the

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hydrogen and steam lines. Temperature control of the humidified stream at the inlet of the fuel cell was achieved by adjusting the temperature of the hydrogen portion of the stream. The hydrogen temperature that is required to provide a desired mixture temperature is produced by proportioning room-temperature hydrogen through or around a specially designed electric heater. The controller dictates the flow proportion necessary to make the actual mixture temperature (feedback) equal to the desired stream temperature (input).

Since the hydrogen-stream pressure drop from the cell inlet to outlet is negligible for the flows at which the cell is operated, cell pressure control was achieved by controlling the setting of the vent-line valve located downstream of the cell. A more detailed description of the test rig plus the humidity sensing instrumentation that was developed in conjunction with the rig are described in references 1 and 2, respectively.

Partial Pressure Regulation

The system shown in schematic form in figure 2 was added to the dynamics rig to test the "partial pressure" regulation concept. This system was set up to allow the cell to be operated either in its normal mode (the O_2 cavity dead-headed on pure O_2) or with the partial pressure regulation system working. In this system the vent line needle valve was used to establish a continuous flow of oxygen through the cell. This is in lieu of a circulating oxygen loop which an actual system application would require. The oxygen and nitrogen servos provide the reactant-inert mixture needed to hold the cell voltage at the regulated value. The valve signals are provided by a servocontrol loop which was breadboarded on the dynamics rig analog computer. The feedback signal to the controller is the actual cell voltage and the setpoint signal the voltage at which the cell is to be regulated.

Total Pressure Regulation

The pressure control loop shown in figure 3 was added to the dynamics rig to test the "total pressure" regulation concept. A servo pressure-controller was breadboarded on the cell oxygen supply to provide closed-loop pressure control which is referenced to cell voltage. The hydrogen control loop of the dynamics rig was, in turn, referenced to the oxygen pressure to provide overall reactant pressure control based on cell voltage.

For both loops, any effect that controller response might have had on the overall response of the regulation system was minimized by using fast response control components. The feedback pressure transducers were fast response strain gage type; the

servovalves were hydraulically actuated and all the servocontrollers were set to provide an optimum response to a step input.

Fuel Cell

A schematic diagram of the type of fuel cell used in this study is shown in figure 4. The electrode assembly consists of an anode, cathode, matrix, electrolyte reservoir plate and a unitizing support frame. The anode and cathode were constructed of a fine mesh silver plated nickel screen which was catalyzed with a platinum/palladium and teflon mixture. The electrolyte reservoir plate was a 100-mil-thick porous nickel sinter and the matrix was a 10-mil sheet of fuel cell grade asbestos. The cell electrolyte was aqueous potassium hydroxide at a concentration of approximately 30 percent by weight. Waste heat was removed from the cell by flowing a liquid coolant through a chamber which covers the back of the hydrogen reactant chamber. The coolant system maintained the cell temperature between 361 and 394 K (190$^{\mathrm{O}}$ and 250$^{\mathrm{O}}$ F).

Product water was removed from the cell by flowing an excess of humidity-controlled hydrogen through the hydrogen supply chamber. In a steady-state mode of operation the product water diffuses from the reaction sites within the anode structure into the electrolyte reservoir. It was evaporated from the electrolyte contained by the reservoir into the hydrogen supply chamber from whence it was removed from the cell by the reactant stream.

PROCEDURE

Partial Pressure Regulation

As part of the ''partial pressure'' regulation test, baseline dilution, purge response, and transient response data were taken. By using the flow control loop shown in figure 2, the oxygen dilution effect on cell voltage was determined by varying the nitrogen-oxygen ratio being supplied the cell. That is, with the cell under load and a constant oxygen purge established, the servocontroller was used in setting various nitrogen-oxygen mixture ratios. The voltage was recorded at each setting and a voltage, reactant-dilution characteristic was obtained. The purge-response of the cell voltage was determined by instantaneously switching from a pure oxygen to a pure nitrogen stream and vice versa. This data was taken to determine the ultimate voltage response that might be attained with a partial pressure regulation system. Also, with the complete servomixing system in operation, several load-step transients were run to demonstrate the quality of control and response of the ''partial pressure'' breadboard loop.

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Total Pressure Regulation

For the "total pressure" system, pressure-voltage characteristic data were taken and transient regulation tests were run. The relation between reactant pressure and cell voltage was determined. Steady-state pressure-voltage data were taken at various cell load levels to map the range of operation for this system. Also, the speed at which load-step induced voltage changes could be regulated was demonstrated with the breadboard loop shown in figure 3.

RESULTS AND DISCUSSION

As stated previously, this study was conducted on the premise that a source voltage regulation system would be designed to work only between the low and nominal levels of the fuel cell design power range. On this basis, for the cell tested the low to nominal load current range is assumed to be from 50 to 200 amperes (100 to 400 ASF). From the cell's voltage-current characteristic, which is shown in figure 5, a variation of 0.100 volt would occur over this range. Thus, to maintain voltage control from the 50- to 200-ampere level, any regulation system would have to be designed to provide 0.100 volt of compensation.

Partial Pressure Regulation

At the 200-ampere level the unregulated cell voltage is 0.81 volt. In a partial pressure regulation system built for this cell, this is the voltage at which the cell would be held. Thus, at the 200-ampere load level and 0.81 volt the cell would be supplied undiluted oxygen reactant. For any load current below this nominal high power level, the cell voltage would tend to increase above 0.81 volt. The function of the regulation system would then be to automatically supply the cell an oxygen stream diluted to the degree required to maintain the cell voltage at its regulated value (0.81 V). The reactant dilution effect on cell voltage is typified by the voltage-dilution characteristic shown in figure 6. These data were taken with the cell supplying a constant 40-ampere load.

Various decay and voltage rise response transients were run to illustrate the fastest attainable response of partial pressure regulation for this cell. The data were taken as voltage decay/buildup in response to an instantaneous switch from pure oxygen reactant to pure nitrogen and vice versa. A typical nitrogen-purge voltage-decay response is shown in figure 7. For this transient the cell was held at a constant 40-ampere load, and an inert purge of 0.264 pph (ten times the O_2 consumption rate) was established. The transient shows that a purge of this magnitude is capable of driving the cell voltage over

its full regulation control range (0.100 V) in approximately 8.5 seconds. At this purge rate the gas in the cell's reactant chamber is replaced in approximately 2 seconds. If this were assumed to be a dead-time lag in the response, the actual voltage decay response of the cell takes 6.5 seconds. In terms of a system application this would be indicative of the fastest full-scale response that might be achieved with a partial pressure regulation system. Obviously, this response could not be attained in practice because of the introduction of controller lags and stability-dictated controller gain settings.

To test the partial pressure regulation technique, the breadboard system shown in figure 3 was set up to obtain closed loop regulation response data. Typical of this data is the 80- to 40-ampere transient shown in figure 8. For this transient the regulation system is seen to make a complete correction in the load-initiated voltage rise in approximately 60 seconds. For this test the cell was supplied a continuous pretransient purge of pure oxygen. A purge flow of four times the oxygen reaction consumption rate at the 80-ampere level (0.053 pph) was set up to simulate the recirculating reactant stream which would be a necessary part of a system employing this type of regulation. A purge programmed with the load step to provide rapid removal of the purge oxygen from the fuel cell supply manifolds was not included. However, in this case the continuous, four stoich purge evacuates the cell's reactant chamber in approximately 4 seconds. In light of the rather slow 60-second regulation response, any effect of the 4-second delay in the removal of the pretransient reactant would appear to be negligible. Integral-proportional control action was programmed into the controller and was set up to produce the optimum response for these transients. However, the system design was carried no farther. In an actual application, it might be expected that this response could be improved. For example, an anticipating or rate sensitive control system coupled with a controllable purge system could be expected to provide an improvement.

An application of the "partial pressure" scheme to an actual fuel cell system would, however, generate a considerable increase in system complexity. First, of all, the reactant used for control would have to be continually circulated through the cell to keep the regulation diluents distributed throughout the reactant chamber. Working in conjunction with this would be the inert-reactant mixing system and a controlled reactant purge. This system would function such that during a transient when a control mixture is being set up, a regulated purge would be established to vent off the mixture set for the pretransient condition. Once regulation is established the purge would be shut off and the inert-oxygen mixture continually circulated to hold the cell voltage at the regulated value. Each time the mixture ratio is changed, the system experiences a loss of inert and reactant. For a typical system load profile the quantity of gas lost in maintaining the proper inert ratio could be expected to be considerably greater than that required for a scheduled reactant purge. This net loss in inert and reactant therefore represents a further disadvantage in applying this type of regulation.

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Total Pressure Regulation

The effect of the total pressure on the cell voltage is typified by the pressure-voltage characteristic shown in figure 9. By again defining the regulation range from the cell current-voltage characteristic to be 0.100 volt, an approximate pressure control range from 11.7 to 44.8 N/cm^2 abs (17 to 65 psia) is defined. The range determined from this curve is only approximate since the pressure-voltage relation is a function of the cell load current.

With the servocontroller of the breadboard loop (fig. 4) optimized in terms of damping and overshoot, various transients were run to test the "total pressure" regulation concept. A typical response for a 50-ampere load step is shown in figure 10. In this transient the cell voltage drops instantaneously from 0.93 to 0.88 volt as the load current is stepped up. Because of controller lags and system gas capacity, it was impossible to provide regulation at the instant a load transient was introduced. However, the system did function to bring the cell voltage back to its regulated value of 0.93 volt in approximately 15 seconds.

To try and determine just how responsive a system such as this might be made, the breadboard design was carried one step farther. A shaping regulator loop to provide voltage regulation for load increases was added to the breadboard to provide regulation from the instant that the transient was introduced to the time when the voltage regulation system gained control. A schematic of this loop, which consists of a battery, electronic voltage regulator and a blocking diode, is shown in figure 11. This system was set up with an 8-millivolt control dead band. That is, it was set to remain inactive until the cell voltage dropped more than 8 millivolts from the regulated value. When this did occur, the electronic regulator of the shaping loop turned on and the battery supplied the portion of the load necessary to keep the fuel cell voltage from dropping more than 8 millivolts from the regulated value. The 8 millivolt drop that was permitted to occur then served as an error signal to the "total pressure" regulation loop and pressure compensation began. As the reactant pressure increased, the fuel cell assumed an increasing amount of the load being carried by the shaping regulator until it was shut off.

At this point the cell was still down 8 millivolts from its regulated value but the pressure regulator continued to act to provide the final correction. Voltage response transients to a 50-ampere load step comparing the system utilizing only pressure regulation to one which includes a shaping regulator are shown in figure 12. These data show that the actual steady-state response time is not greatly improved; however, the cell voltage drop is held to only 8 millivolts with a minimal amount of auxiliary energy (36 watt seconds for this transient).

As was the case for "partial pressure" regulation, incorporating "total pressure" regulation into a fuel cell system would require some accommodation. For example, if this method were applied to the type of fuel cell in which product water rejection is

regulated by controlling the vapor pressure of a circulating reactant, the control action of the voltage regulation system would have to be compensated for. That is, any change in total reactant pressure would affect the rate of water rejection and thus a correction would be required to maintain control. A typical technique for setting the system vapor pressure is to control the condensation temperature of a product water condenser. This temperature could be used as a compensating parameter to negate the effects of the reactant pressure changes introduced by the voltage regulation system. In current space power fuel cells it would appear that this could be accomplished without a prohibitive increase in system complexity.

In comparing the two methods tested, the "total pressure" system would appear to be the more favorable. In terms of controllability the reactant ambient pressure provides a more positive control parameter than does the reactant partial pressure and hence a high degree of control sensitivity is easier to attain. In terms of complexity it would be easier to accommodate the varying pressure of the "total pressure" technique in a system design than to incorporate a controlled purge system and a rather complex inert-reactant mixing system required by the "partial pressure" system. The basic response of the total pressure parameter is better because a pressure change can be transmitted to the cell reaction much quicker than can a composition change which is mass transport limited. Considering the system efficiency in terms of the relative gas consumption of the two systems, the partial pressure regulator would be expected to demand considerably more gas in going from one set point to another. To attain the best response for this system, any change in set point would require that the previous mixture be completely vented from the cell. On the other hand to get rapid response from the total pressure system for a step up in power would require no venting while a step down would require only a depressurizing vent. The gas lost in depressurizing could be expected to be significantly less than that vented to change compositions in the partial pressure system.

One situation which would favor the application of partial pressure regulation would be that in which the system weight increase generated by the requirement that the total pressure method operate at high pressure would overshadow the response and efficiency advantages sited previously.

A favorable characteristic common to both systems is the fact that continuous, active control of cell performance would be attained. That is, aside from compensating for transient changes, the controllers would be functional during the steady-state mode of operation to automatically adjust for any degradation in cell performance.

CONCLUDING REMARKS

Two techniques were explored as possible methods for source voltage regulation of fuel cells. From the testing that was done both methods were found to be workable. However, for application to present day space power fuel cell systems the method that uses reactant ambient pressure for voltage control appears to be more amenable than does the method which controls voltage by throttling the cell reaction with a controlled inert-reactant mixture. In terms of overall applicability the total pressure concept would appear to be the more favorable method since it could provide better controllability with less complexity, better transient response, and probably better efficiency in terms of specific reactant consumption.

Lewis Research Center,
  National Aeronautics and Space Administration,
    Cleveland, Ohio, February 3, 1975,
      506-23.

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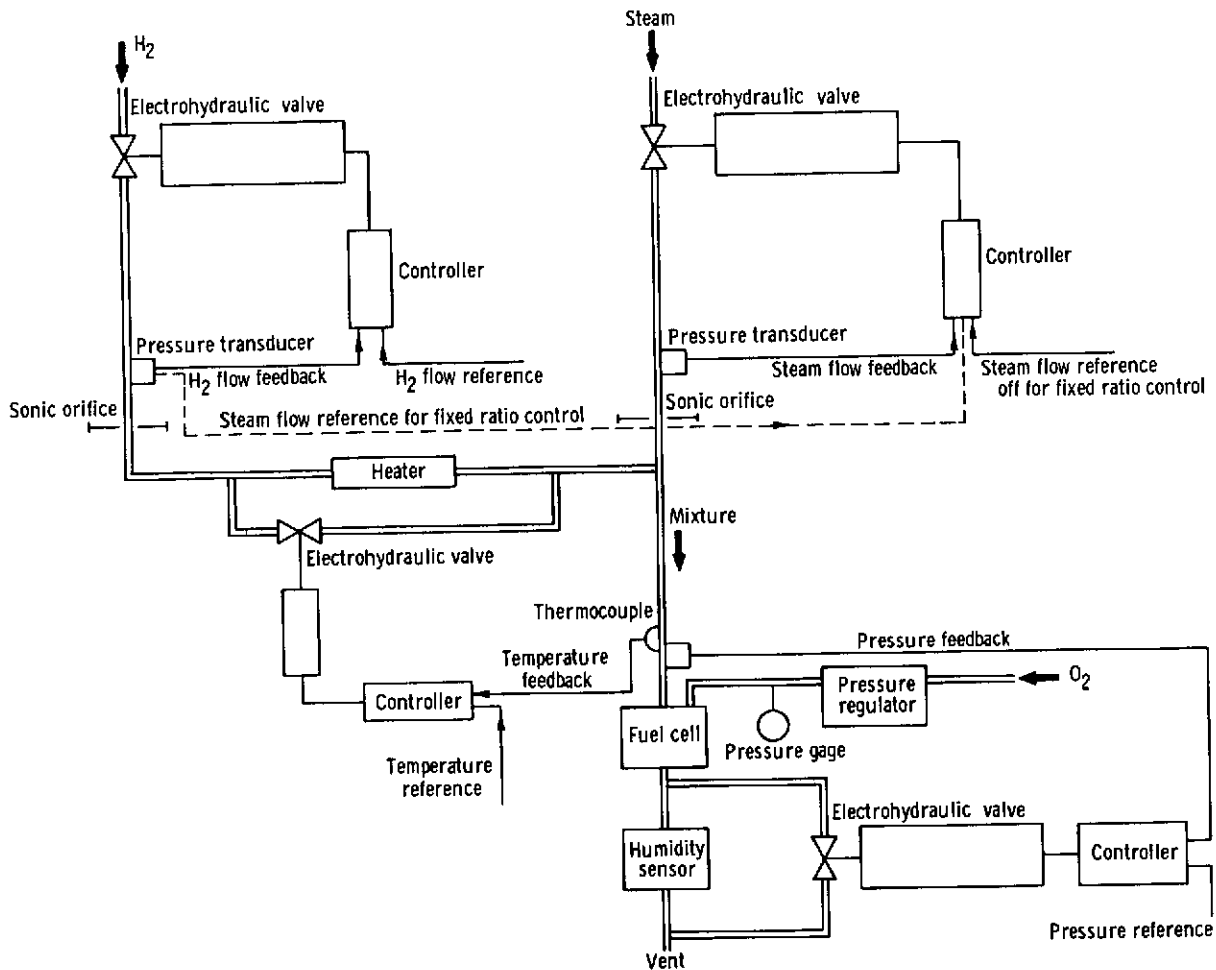
Figure 1. – Schematic diagram of fuel cell dynamics test rig.
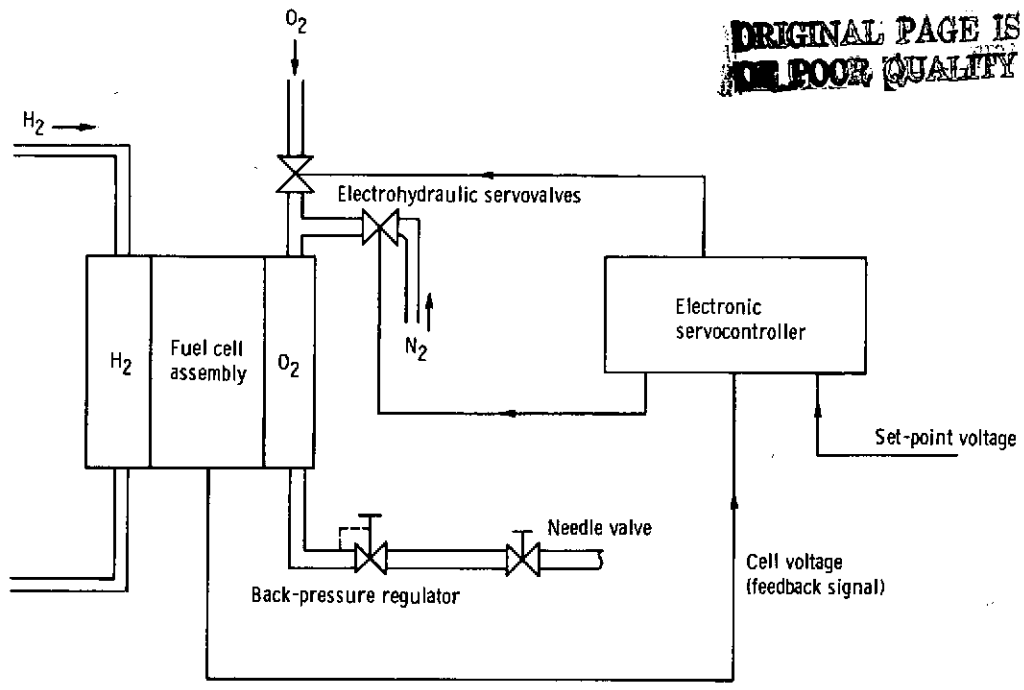
Figure 2. - Test loop schematic (partial pressure regulation).
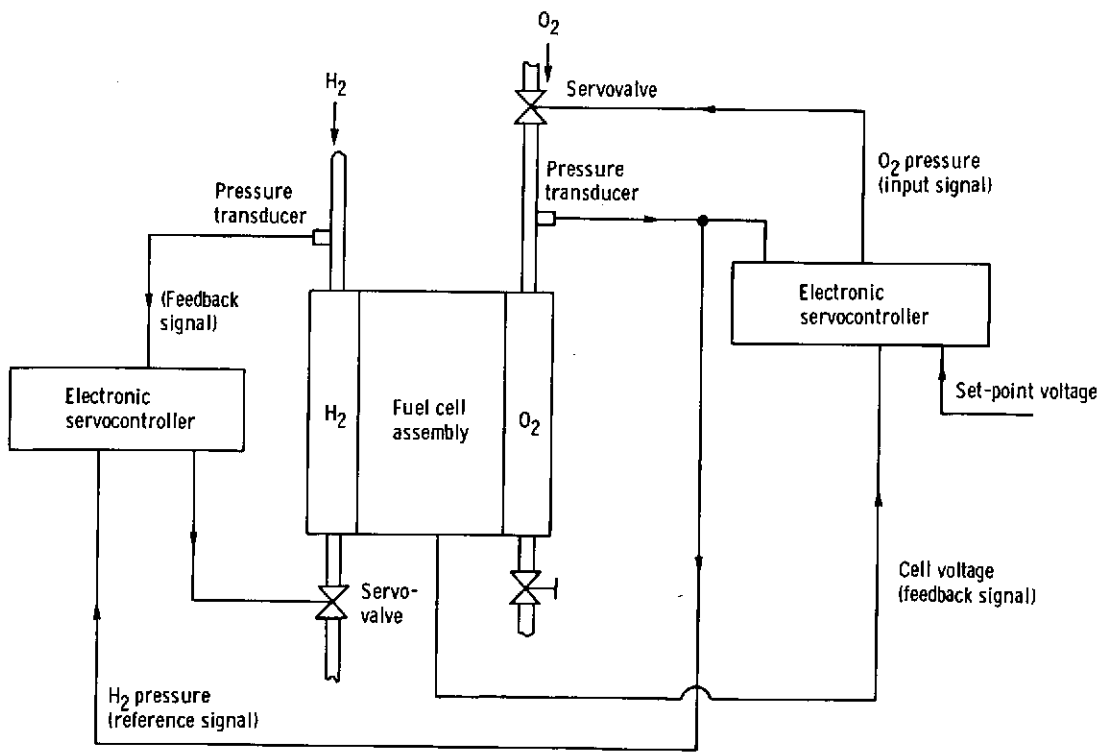
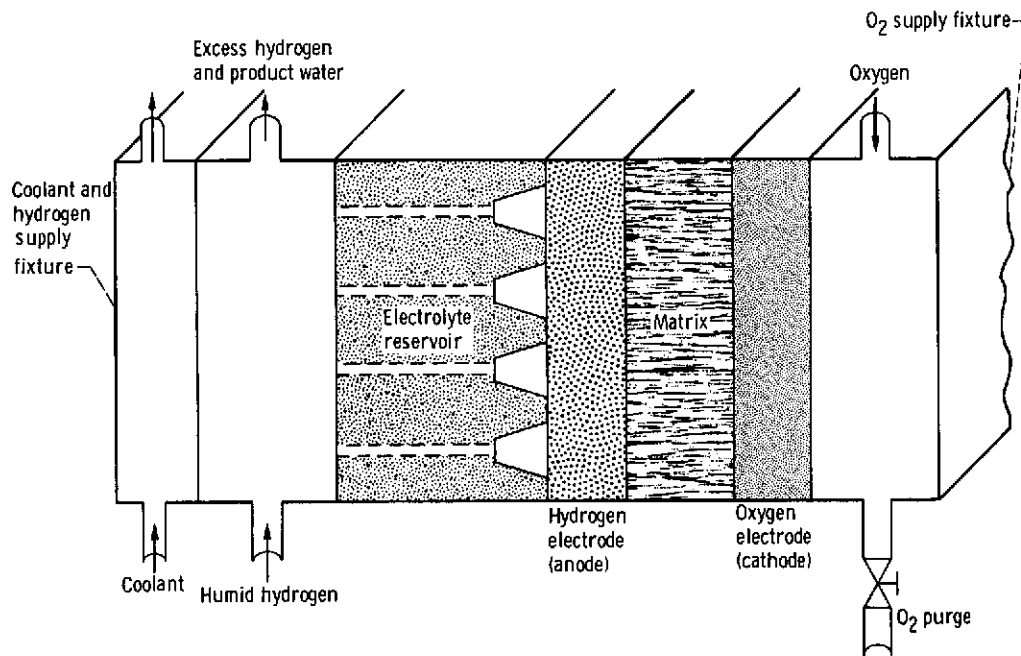Figure 3. - Test loop schematic (total pressure regulation).
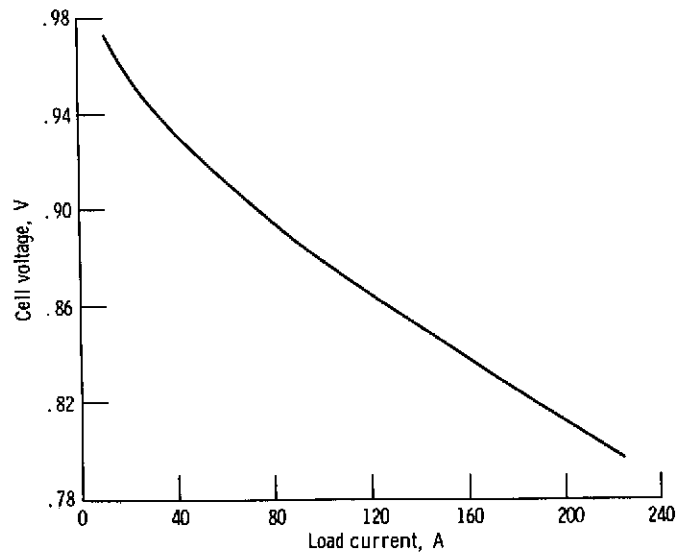
Figure 4. - Fuel cell schematic.

Figure 5. - Fuel cell current-voltage characteristic. Operating conditions: reactant pressure, 5.51 N/cm^2 gage (8 psig); coolant inlet temperature, 361 K (190^0 F); humidified hydrogen (reactant supply mixture of a 12 pph of H$_2$ 0.34 pph of water vapor).
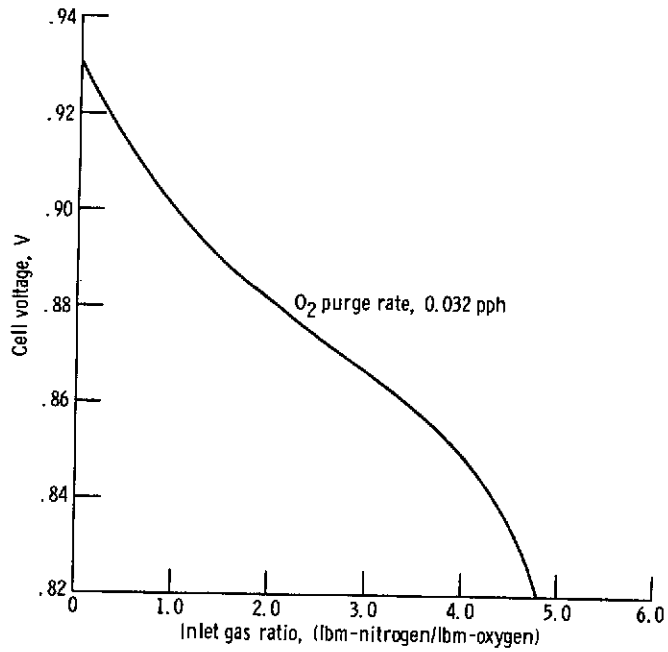
Figure 6. - Fuel cell nitrogen-dilution voltage characteristic. Operating conditions: cell load, 80 amperes per square foot (O_2 consumption rate, 0.026 pph); continuous purge operation.
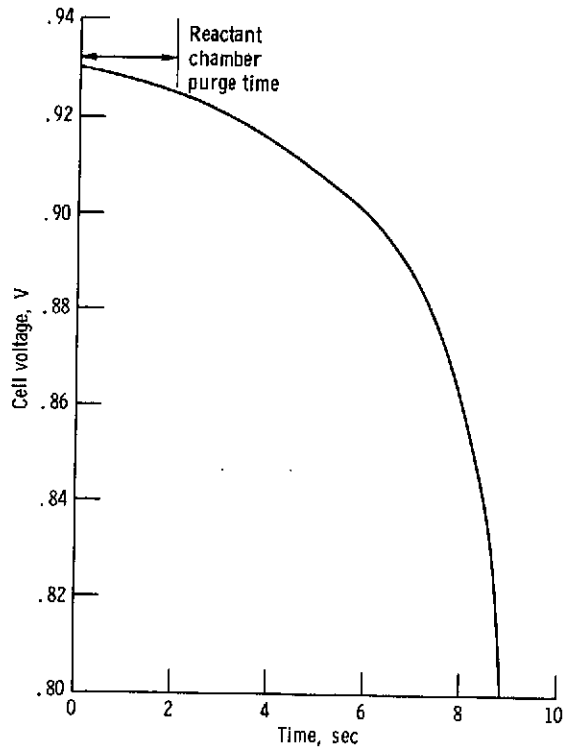
Figure 7. - Fuel cell decay response (N_2 purge). Operating conditions: cell load, 80 amperes per square foot; pure O_2 reactant replaced by pure N_2; purge rate, 10 times consumption.

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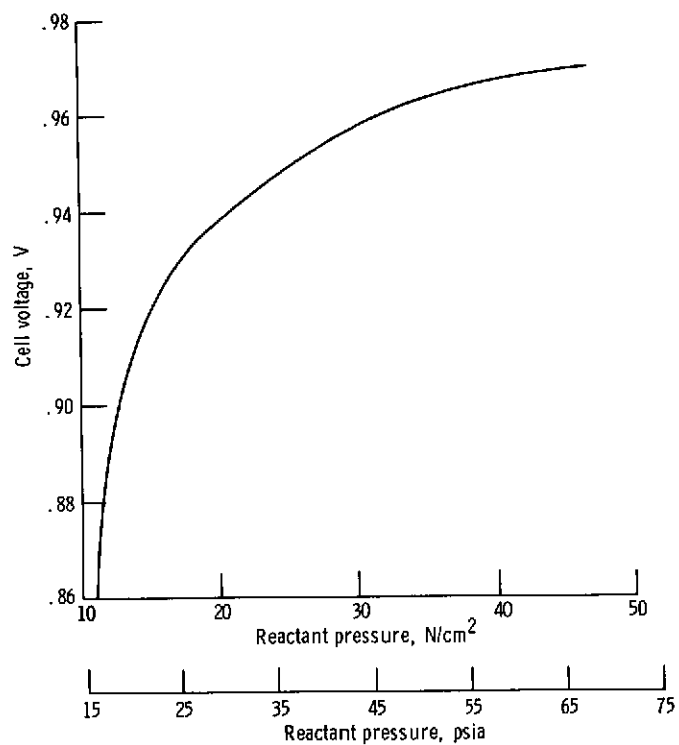
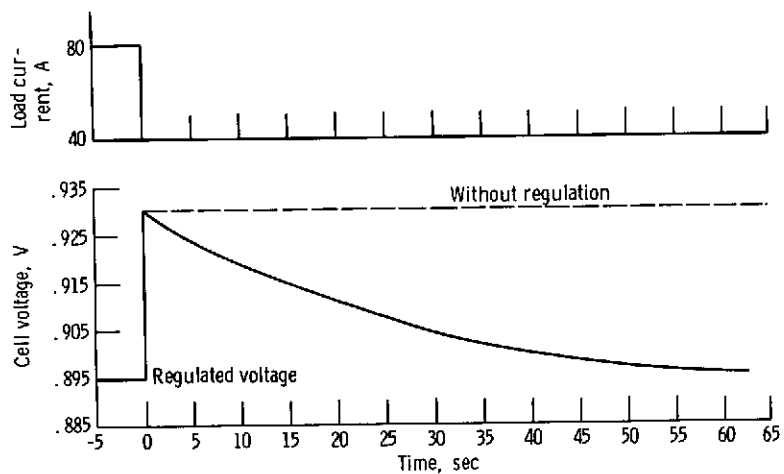Figure 9. - Fuel cell pressure-voltage characteristic. Cell current, 50 amperes.

Figure 8. - Voltage regulation test (partial pressure control). Operating conditions: cell supplied pure O_2 at 80-ampere level; pretransient purge set at four stoich (0.053 pph); maximum flow of either component limited to 0.10 pph.
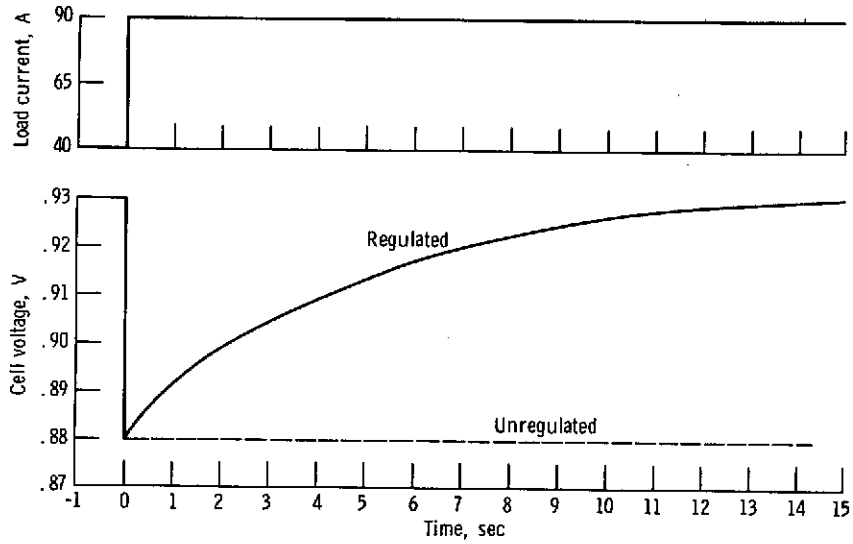
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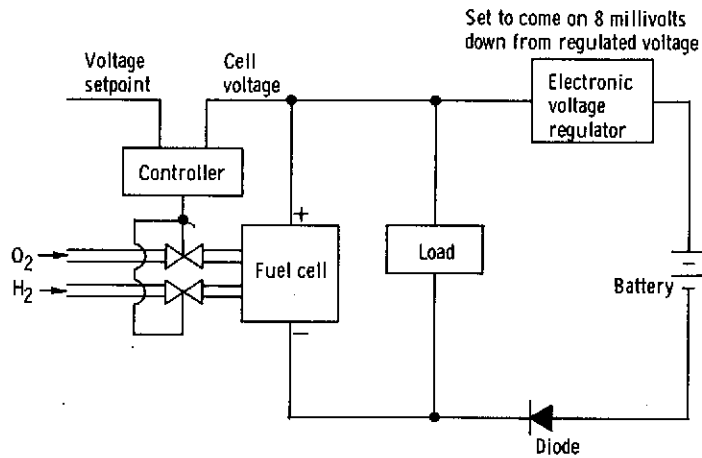Figure 10. – Voltage regulation test (total pressure control).

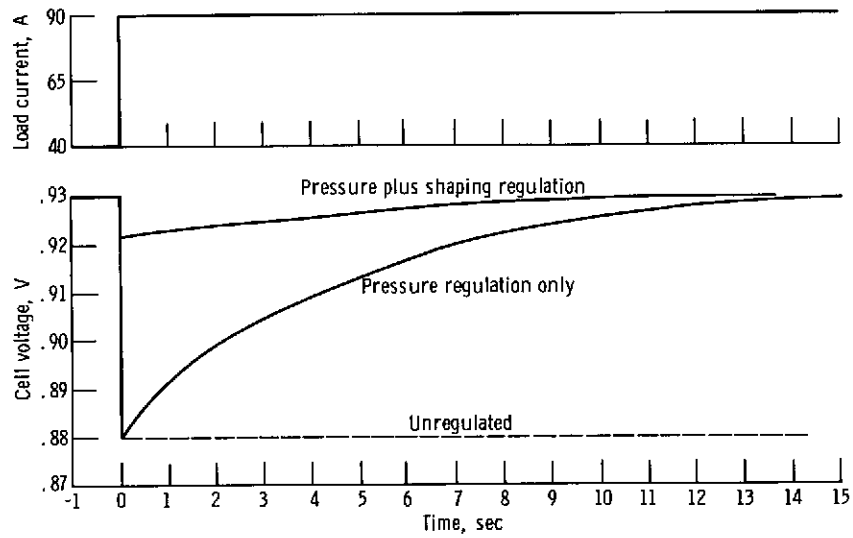Figure 11. – Pressure plus shaping regulation (for load increases).

Figure 12. - Voltage regulation test (total pressure control plus shaping regulator). (Shaping regulator supplies 36-watt-seconds of energy during transient.)