NASA TECHNICAL MEMORANDUM

NASA TM X-2923

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1973

1. Report No. NASA TM X-2923	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MONITORING AND CONTROL OF FUEL-CELL SYSTEM BY DIGITAL COMPUTER		5. Report Date October 1973
		6. Performing Organization Code
7. Author(s) Norman H. Hagedorn and Ralph D. Thomas		8. Performing Organization Report No. E-7475
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 502-25
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The computer was programmed to handle data, perform limit checks, control normal operation, take corrective actions, and initiate shutdown for a fuel-cell system. The system was operated under computer control for periods up to 30 hr. The adequacy of the programming and interfacing techniques used was verified.

17. Key Words (Suggested by Author(s)) Fuel-cell systems Computer control		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 9	22. Price* Domestic, $2.75 Foreign, $5.25

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

The purpose of this experimental program was to develop the techniques and capabilities necessary for using a digital computer to monitor and control a fuel-cell system. The computer was interfaced to a 250-watt fuel-cell system which had been outfitted with transducers and control devices. A program and subroutines were written for computer control of data acquisition and printout, limit checking, "housekeeping" chores, corrective actions, and emergency shutdowns. The fuel-cell system was operated under computer control for periods of up to 30 hours.

The reliability of the computer, the suitability of the programs, and the adequacy of the interfacing techniques were all verified. During the experiment it became evident that more sophisticated software for time sharing would be desirable. This software is called for because the computer must simultaneously service both the fuel-cell system and six single-cell test stands.

INTRODUCTION

Because of planned long-term tests of fuel-cell systems, it has become desirable to use a small-scale, general-purpose digital computer for test surveillance and control. To develop the techniques for such use of the computer, a 250-watt fuel-cell system was modified to interface with it (ref. 1). Transducers on this system provide data inputs to the computer. Relays and stepping motors on the system respond to control signals from 31 computer-activated electronic switches.

A computer program was then written for the handling of data, the checking of limits, the performance of such housekeeping tasks as load changing and reactant purging, and the taking of corrective action when limits were exceeded. In addition, a subroutine which could be incorporated into the main program was written for a specialized operation called volume optimization.

The main program, subroutine, and computer performance were evaluated by placing the computer in control of the operating fuel-cell system. This report discusses the operations performed by the computer and the results of the test program.

DESCRIPTION OF COMPUTER AND DATA HANDLING SYSTEM

Hardware

Figure 1 shows a block diagram of the computer-controlled data system and associated fuel-cell tests. The entire system is controlled by a small-scale digital computer, equipped with memory extension modules totaling 12, 000 words of core. External memory is provided by a 262,144-word disk. The disk is used as a library of various applications programs, constants, and variables which can be read into the core and executed at high speeds. This facilitates limited but useful time sharing of the system. The disk is also used to store executive programs, table generators, and so forth. These may be reloaded quickly into the core in the event that a program is lost. A high-speed paper-tape reader also provides for rapid loading of programs into the core from program tapes. The system is equipped with 31 computer-program-controlled switch closure lines that are used to activate relays, alarms, and other experiment control hardware.

Also shown in figure 1 are standard data acquisition components that include a 200-channel reed relay scanner; a six-digit autoranging integrating digital voltmeter; a digital clock that outputs day of the year and hours, minutes, and seconds of the day; a system coupler; and a teletype machine that prints or punches data.

Software

The system executive software package is made up of three component parts: (1) the system monitor, which controls the basic flow of the data through the system and allocates machine time according to priorities; (2) FOCAL-X, an on-line, conversational interpretive language program used to communicate with the computer; and (3) a floating-point arithmetic package that is shared by both the system monitor and FOCAL-X.

Used in conjunction with the executive software, and written in FOCAL-X, are a table generator program and the specific applications programs written for each test. The table generator permits the operator to generate, examine, modify, and delete a number of control and data list entries by using the teletype keyboard.

Typical Two-User System Operation

A software clock in the computer is driven by pulses from the digital clock by means of the system coupler (fig. 1). After a preset time interval has elapsed, system control transfers from an idle loop to a subroutine in the applications program that is resident in the computer text buffer. This subroutine initiates a data scan as specified by the data acquisition table, programs the integrating digital voltmeter, converts the new data to engineering units, and stores them in the core. If the resident applications program is for test A, that program is executed. Limit checks, terminal calculations, control functions, out-of-limit messages, and data output for test A are performed as specified in the program. The last statement in program A reads applications program B (stored on the disk) into the text buffer, overlaying program A. When the readin of program B is completed, the computer automatically enters its idle loop and waits for the time interval to elapse again. After program B has been executed, program A is again read into the core and executed. Processed data and control messages from the two tests are printed out on the teletype. Should one test be shut down by the computer, a flag is set and the application program of that test is no longer executed. The time interval chosen for tests A and B was 3 minutes, which resulted in a total turn around time of 6 minutes for each program. This time limitation was imposed by the relatively slow teletype output device.

MAIN PROGRAM OPERATIONS

Data Handling

The transducer data transmitted to the computer represented fuel-cell voltages, current, reactant pressures, electrolyte vapor pressure, and cell temperatures. Immediately after a data scan, the data were converted to engineering units. No conversion was required for the cell voltages, which were measured directly. Pressure-transducer signals were preconditioned and merely required a multiplication by 10 by the computer. Cell current was obtained by multiplying a shunt voltage drop by the shunt factor. Thermocouple voltages were converted to temperature readings by use of an empirical second-order equation.

An important parameter, the fuel-cell electrolyte concentration, was obtained by trial and error from the Antoinne equation (ref. 2)

$$\log p = A - \frac{B}{C + T} \tag{1}$$

and the measured values of electrolyte vapor pressure p and fuel-cell temperature T. The coefficients A, B, and C are functions of electrolyte concentration. Values of these coefficients were stored in memory for an electrolyte concentration range of 32 to 38 weight percent in 1/2-percent increments.

The printout of data in engineering units occurred 6 minutes before and 6 minutes after each programmed change in the fuel-cell load. The printout included the elapsed time since program initialization, the accumulated ampere-hours since initialization, the electrolyte concentration, the reactant pressures, the electrolyte vapor pressure, the fuel-cell temperatures, the fuel-cell voltages, and current.

Normal System Control

Three time-based control functions were performed by the computer. These were the rejection of water product from the system, the purging of inert gases from the reactant cavities, and the changing of the fuel-cell electrical load. Control was achieved by the closing of electronic switches by the computer. These switch closures caused the energization of the power relays in the control system. In the case of water rejection or reactant purging, the energized relay activated solenoid valves on the fuel-cell engine, which caused the desired function to be performed. To change the electrical load, the energization of the appropriate power relay brought about a change in the bias voltage to an electronic constant-current load bank.

Limit Checking and Corrective Operations

After fuel-cell operating data were converted to engineering units they were examined to see whether they fell within prescribed limits. If not, either corrective action was taken or the engine was shut down. Those conditions leading directly to shutdown, with no intervening attempt at correction, were low fuel-cell temperature, high or low reactant pressure levels, and a pressure difference between the reactants.

It was anticipated that fuel-cell overtemperature would most likely occur at the high current levels, that is, those of 60 amperes or more. The computer program, therefore, called for a reduction of load current to 40 amperes whenever the cell temperature exceeded 91° C (195° F) but was less than 93° C (200° F). All subsequent programmed load changes were then bypassed, but the remainder of the program remained operative. If the fuel-cell temperature exceeded 93° C (200° F), the computer initiated the shutdown sequence.

If the calculated electrolyte concentration was outside the range 32 to 38 weight percent, the powerplant was shut down. If it was within that range, but differed from a prescribed value, the electrolyte concentration was adjusted by a change in the pressure at which product water was removed from the fuel cells. This pressure change was effected by sending a chain of pulses from an internal switch, through a power relay, to a stepping motor geared to the shaft of a pressure regulator. The necessary number of pulses was determined by comparing the measured electrolyte vapor pressure with the calculated vapor pressure for the desired electrolyte concentration. The later value was obtained from equation (1) by using the measured temperature and the Antoinne coefficients A, B, and C for the desired concentration. The pressure difference was then multiplied by the calibration factor for the stepping-motor - gear - pressure-regulator combination to obtain the necessary number and polarity of pulses.

The measured fuel-cell voltages were compared with calculated values for the existing current level. These values were derived from a linearized form of the fuel-cell polarization curve which gives voltage as a function of current. If the measured voltage was more than 50 millivolts below the calculated value, the reactant cavities were given two purges, separated by a 6-second interval. If the measured voltage remained low during the three data scans following the double purge, the fuel-cell load was decreased 20 amperes. Normally scheduled load changes were bypassed from then on. If the voltage remained low at this new current level, the whole sequence, starting with the double purge, was repeated. Whenever the load decrease caused by low fuel-cell voltage was from a current level of 20 amperes to open circuit, the computer initiated the system shutdown sequence.

Volume Optimization

One characteristic of fuel cells of the type used in this experimental program is that there exists an optimum volume of electrolyte which results in maximum fuel-cell voltage for any given current level. Operation on the wet (greater volume) side of this optimum causes a loss of voltage which is reversible and can be recovered by going to a drier condition. Operation on the dry side, however, results in a partly irreversible voltage loss. Therefore, a secondary computer program, to maintain the electrolyte volume in the fuel-cell system slightly on the wet side of the optimum value, was written. This program could have been incorporated into the main program as a subroutine. However, it was evaluated by using it, instead of the main program, to control the fuel-cell system.

In operation, the volume optimization program first calculated the existing electrolyte concentration. It then determined how much the product water removal pressure would have to be changed in order to decrease the electrolyte concentration 1 weight percent. Next, as previously described, it effected that change. If the fuel-cell voltage equilibrated at a higher level, the sequence was repeated until no further improvement occurred. Then one final change, equivalent to a decrease in concentration of 1/2 percent, occurred.

If, however, the first decrease in concentration resulted in a voltage loss, the program caused a step-by-step increase in concentration until no further voltage improvement occurred. Then, as before, one final step of 1/2 weight percent was taken back toward the wet side.

RESULTS

Except for a few program debugging problems, the performance of the computer while controlling the fuel-cell system was satisfactory. The longest period of uninterrupted computer control was 30 hours, and it was terminated for a weekend. During the experimental evaluation, every type of out-of-limit system performance which had been provided for in the main program occurred. In all instances the proper corrective action was taken, or when called for, shutdown was initiated.

The primary drawback in using this computer to control a test program is a certain degree of inflexibility. This inflexibility results from the nature of the executive program software which was purchased with the computer. The executive program was intended to manage one fuel-cell test. However, at the same time the test which is the subject of this report was being run, the computer was also being used to monitor and print out data for a group of six single-cell test stands. Therefore, when the applications programs for the computer were being written, two options were available: write one "super" program within which the instructions for the two experiments would be interwoven, or write two separate programs and alternately store them on and retrieve them from disk storage. The latter approach was taken.

It then became necessary to allow adequate time, when each program was called, for the data scan, unit conversions, limit checks, and printout. All these processes were slow, with printout being by far the slowest. Limit checking could have been made considerably faster by having the checks made on raw data, rather than first converting the data to engineering units. Time also could have been saved by allowing time for unit conversions and printout only when printout was actually scheduled to occur. However, it was decided instead to allocate 3 minutes alternately to each program. Thus, 6 minutes elapsed between calls for a given program.

This 6-minute interval, therefore, became the major timing element in the main program for the fuel-cell powerplant. Operations such as reactant purging, which were scheduled to occur after the passing of a given number of ampere-hours, occurred instead during the 6-minute interval initiated after the correct period had elapsed. By the same token, whenever of of the operating parameters of the fuel-cell system fell outside its limits, corrective action did not occur until as late as 6 minutes later.

These shortcomings of the executive software, while not causing any problems during this experimental program, did serve to point up the desirability of having a much more sophisticated executive program for time sharing. This would allow for more flexibility and efficiency in using the computer as a multitest controller. It would also decrease the hazard of an incipient failure mode being undetected until too late.

SUMMARY OF RESULTS

A program to use a small-scale digital computer for the surveillance and control of an operating fuel-cell system has produced the following results:

1. The general ability to program the computer to monitor and control a fuel-cell system has been developed.
2. The basic techniques for interfacing the computer to a fuel-cell system for control purposes have been established.
3. The ability to use the computer to monitor and control two different test programs concurrently has been demonstrated.
4. The desirability of acquiring software for more efficient time sharing has been made evident.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 3, 1973,
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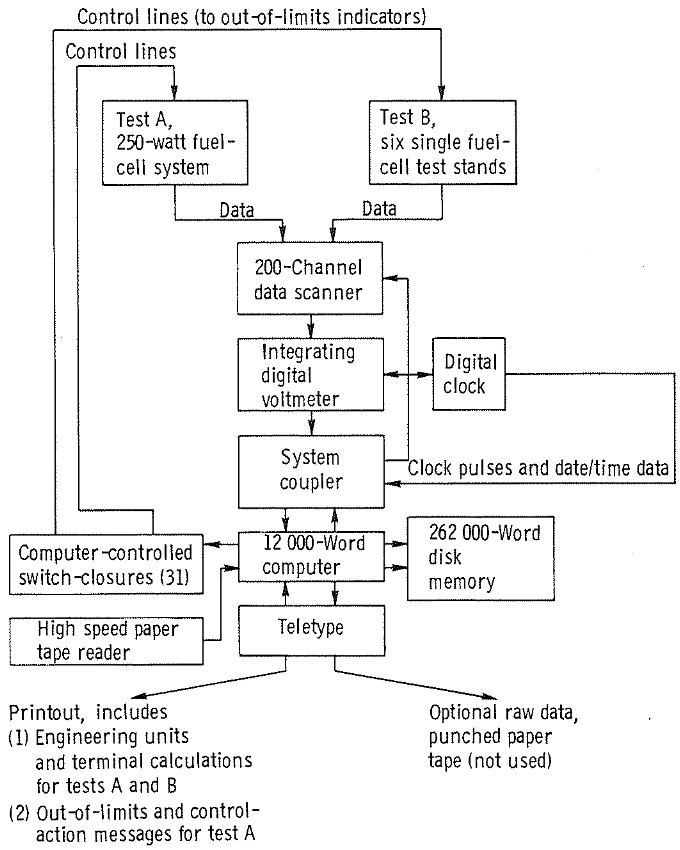

Figure 1. - Block diagram of computer-controlled fuel-cell tests.

NASA-Langley, 1973 —— 3 E-7475

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