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INFORMAL REPORT

HEAT-ACTUATED METAL HYDRIDE HYDROGEN COMPRESSOR TESTING

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Michael Piraino and Philip D. Metz

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Prepared for

ELECTRIC POWER RESEARCH INSTITUTE
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HEAT-ACTUATED METAL HYDRIDE HYDROGEN COMPRESSOR TESTING

FINAL REPORT

RP 1086-20

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EXECUTIVE SUMMARY

Electric utilities use hydrogen for cooling turbine generators. The majority of the utilities purchase the gas from industrial gas markets. On site electrolytic hydrogen production may prove advantageous both logistically and economically.

In order to demonstrate this concept, Public Service Electric and Gas Co. (PSE&G) and EPRI installed an electrolyzer at the Sewaren (NJ) station. To compress the gas, PSE&G purchased a heat-activated metal hydride compressor from Ergenics, Inc.

This report describes closed- and open-cycle tests conducted on this metal-hydride hydrogen compressor. Test systems, plans, methodologies, and results are presented. A brief discussion evaluates these performance results, addresses some of the practical problems involved with electrolyzer-compressor interface, and compares the costs and benefits of metal hydride versus mechanical hydrogen compression for utility generator cooling.

How The Metal Hydride Hydrogen Compressor Works

The Ergenics metal hydride hydrogen compressor consists of two essentially identical circular beds, each containing four stages (Figure S-1). These stages contain different compositions and weights of rare earth/nickel/iron/aluminum alloys and are designed for operation over different pressure ranges. The compressor is operated by alternately running hot and cold water through the water jackets surrounding each set of hydride beds.

Hot water is obtained from two 120-gallon hot water heaters; cold water is obtained directly from the main water supply. The flow of water is controlled by electrically operated solenoid valves (as shown in Figure S-1).

When cold water is passed through bed A, the low temperature favors adsorption of hydrogen. At the same time, hot water is passed through bed B, where high temperature favors hydrogen desorption. As a result, hydrogen flows from stages 1, 2, and 3 in bed B to stages 2, 3, and 4 in bed A. During this time, hydrogen adsorbs onto

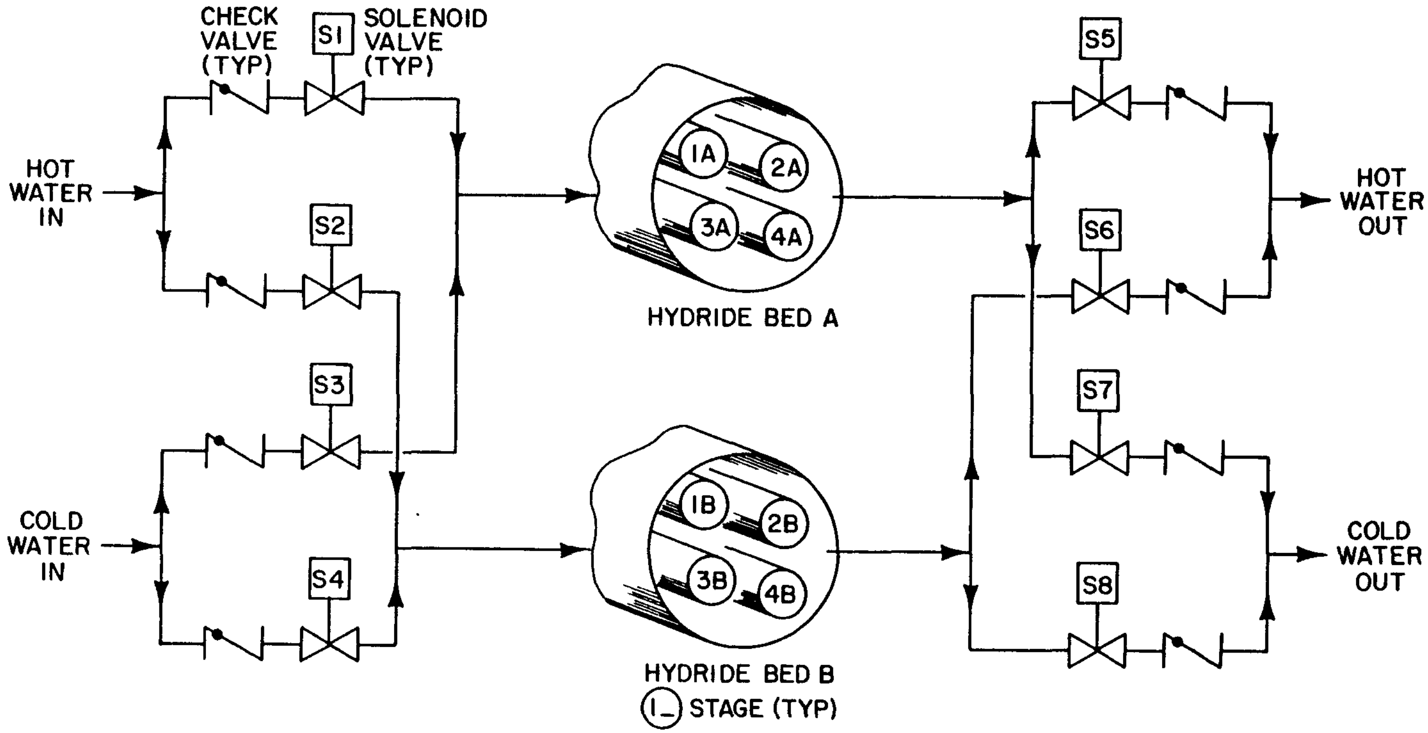

Figure S-1. Four-Stage Metal Hydride Hydrogen Compressor Water Flows stage 1 in bed A from the hydrogen inlet line and stage 4 in bed B desorbs hydrogen to the compressor outlet. After half of the compression cycle time, the hot and cold water flows are switched so that the stages in bed A now desorb while the stages in bed B adsorb hydrogen. A continuous flow of hydrogen is produced by this cycling of temperature in the two beds.

Closed Cycle Compressor Test Results

Closed-cycle compressor tests were conducted in which the compressor recirculated purchased bottled hydrogen gas. These tests have two objectives:

- Characterize compressor at on- and off-design operating conditions.
- Identify optimal operating conditions.

A matrix of 80 sets of test conditions was developed measuring the sensitivity of hydrogen throughput and efficiency to changes in hydrogen pressures, water flow rates and temperatures, and cycle time. The results comprise a comprehensive "performance map" of the compressor.

The tests indicated that hydrogen throughput is maximized at a 2-3 minute cycle time. Compressor efficiency is maximized at roughly a 6-minute cycle time at which point hydrogen adsorption is complete. Both compressor throughput and efficiency are increased significantly by increasing hot water temperature and flow rate, over the ranges examined.

Open Cycle Compressor Test Results

Open cycle compressor tests were conducted in which the compressor was supplied by the BNL Solid Polymer Electrolyte electrolyzer with some bottled gas augmentation. The purpose of these tests is to characterize the compressor--in terms of performance and any operational problems--using electrolytic hydrogen. A test system was built, including surge tanks and gas purification equipment, to interface the compressor with the BNL SPE electrolyzer system. The test program consisted of a small set of parametric tests based on closed-cycle test results, followed by a 5-day continuous test at optimal operating conditions.

The open cycle test system performed satisfactorily. Open cycle parametric test results were consistent with the closed cycle results and quite repeatable. Long-term test results are tabulated below.

Table S-1

LONG-TERM TEST RESULTS

Quantity	Purchase Specifications	Average Test Value
Hot water inlet temperature	185°F	189°F
Hot water outlet temperature	-	169°F
Cold water inlet temperature	77°F	56°F
Cold water outlet temperature	-	74°F
Hydrogen Inlet Pressure	115 psia	103 psia
Hydrogen Outlet Pressure	1015 psia	1029 psia
Hydrogen Flow Rate	3 SCFM	2.6 SCFM
Compressor Efficiency	-	2.1%*
Hydrogen Dewpoint		-74°F (2 ppm)

*The compressor efficiency is defined as the ideal isothermal work done in compressing the gas divided by heat lost in the hot water stream. See Appendix A.

General Conclusions

Aside from a single breakdown due to a defective heat exchanger end plug, the metal hydride compressor operated very reliably for on the order of 350 hours (5600 cycles) during testing at HTEC. No operational difficulties were encountered. Test results were consistent and repeatable (see Table 1-1). Compressor hydrogen throughput at rated conditions was 2.6 SCFM, about 14% below the 3.0 SCFM specification, during the 120-hour long-term test. Compressor efficiency averaged 2.1%.

The approach used to interface the metal hydride compressor with the BNL SPE electrolyzer appears successful. The use of low-pressure surge tanks to stabilize hydrogen pressure despite the transient flow mismatch between the electrolyzer and compressor was satisfactory. The hydrogen purification system used also appears to be satisfactory. For long-term operation it is recommended that 2 dryers be installed in parallel, each with isolation valves and unions. Thus when one is depleted it can be removed from the system, replenished, and reinstalled without halting operation.

A simple economic analysis was conducted of the cost/benefits of metal hydride versus mechanical hydrogen compression. The metal hydride compressor, due to its lower capital cost and O&M expense compresses hydrogen at lower annualized cost for low energy prices. However, due to its low efficiency, the cost of compression of the hydride compressor is very sensitive to energy cost. Compression costs for the mechanical compressor, on the other hand, are quite insensitive to energy cost because of its far higher efficiency. For example, as illustrated in Figure S-2, the annualized cost to compress a thousand standard cubic set of hydrogen with a metal hydride compressor is $.68 when the energy is free, and $9.64 when the energy costs $.1/kWh. The annual compression costs for a thousand standard cubic set of hydrogen using a mechanical compressor is $2.29 when the energy is free, and $2.75 when the energy costs $.1/kWh.

The main benefit of using a metal hydride compressor over a mechanical compressor is reliability. The mechanical compressor at PSE&G was inoperate 75% of the time due to leaks in the seals.* The metal hydride compressor tested at BNL experienced no operating difficulties after the inadvertent use of carbon steel instead of stainless steel heat exchanger plugs was corrected.

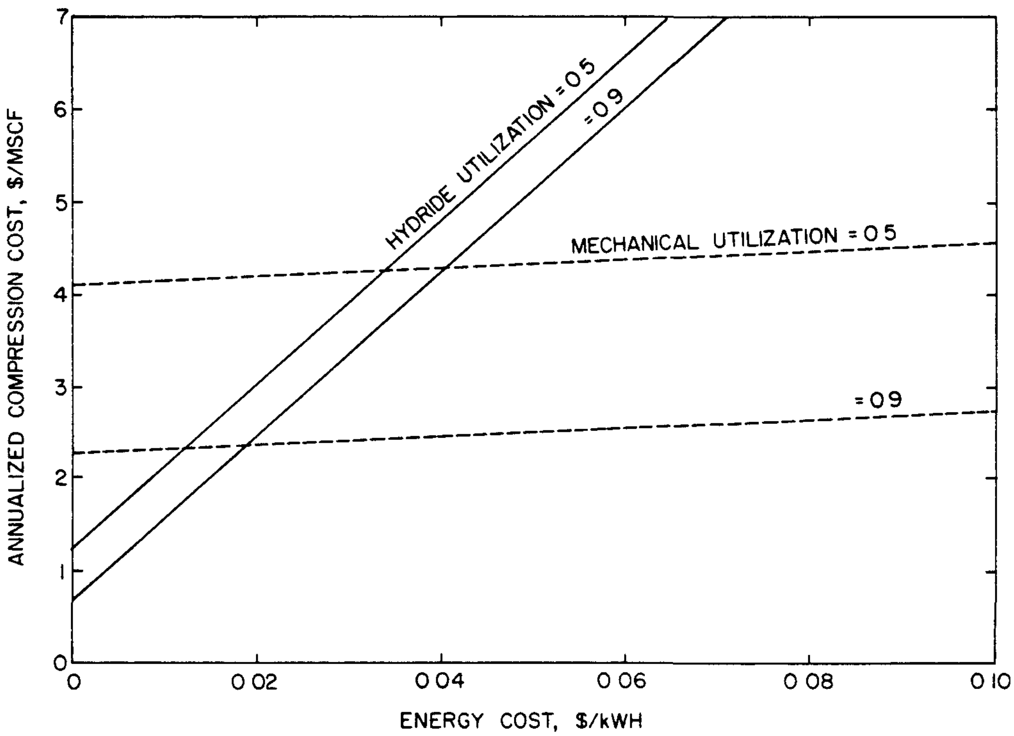

Figure S-2. Economic Comparison of Mechanical Versus Metal Hydride Hydrogen Compressors.

*Conversation with Angela Graham of Public Service Electric and Gas Company (3/86).

Section 1

INTRODUCTION

SCOPE OF THIS REPORT

This report describes closed- and open-cycle tests conducted on a heat-actuated metal hydride hydrogen compressor. Test systems, plans, methodologies, and results are presented. A brief discussion evaluates these performance results, addresses some of the practical problems involved with the electrolyzer-compressor interface, and compares the costs and benefits of metal hydride versus mechanical hydrogen compression for utility generator cooling.

HYDROGEN TECHNOLOGY EVALUATION CENTER AT BROOKHAVEN NATIONAL LABORATORY

Figure 1-1 is a cutaway view of the HTEC building. Room 1 is a clean room housing the data acquisition/control subsystem which operates and monitors the Solid Polymer Electrolyte (SPE) electrolyzer. Room 2 is a small utility room containing the power conditioning equipment for the electrolyzer. The SPE electrolyzer itself, shown in Figure 1-2, is located in room 3 along with its associated water treatment system, hydrogen dryer, and safety devices. Room 4 contains the test system used for characterizing heat-actuated metal-hydride hydrogen compressors. A walkway is provided for visitors to view the facility. Outside the building is a 5 kW photovolatic array which partially powers the SPE Electrolyzer.

METAL HYDRIDE HYDROGEN COMPRESSOR TESTING AT HTEC

Hydrogen gas is widely used by electric utilities for generator cooling. Ordinarily, this gas is supplied via the normal merchant hydrogen channels. However, on-site generation of hydrogen may have logistical and economic advantages.

For this reason, Public Service Electric & Gas Company (PSE&G) a New Jersey utility, and the Electric Power Research Institute (EPRI), are evaluating the on-site generation of hydrogen using an SPE electrolyzer at its Sewaren generating station. To compress the gas produced by the electrolyzer, PSE&G has purchased a heat-actuated metal hydride hydrogen compressor from Ergenics, Inc., of Wyckoff, New Jersey.

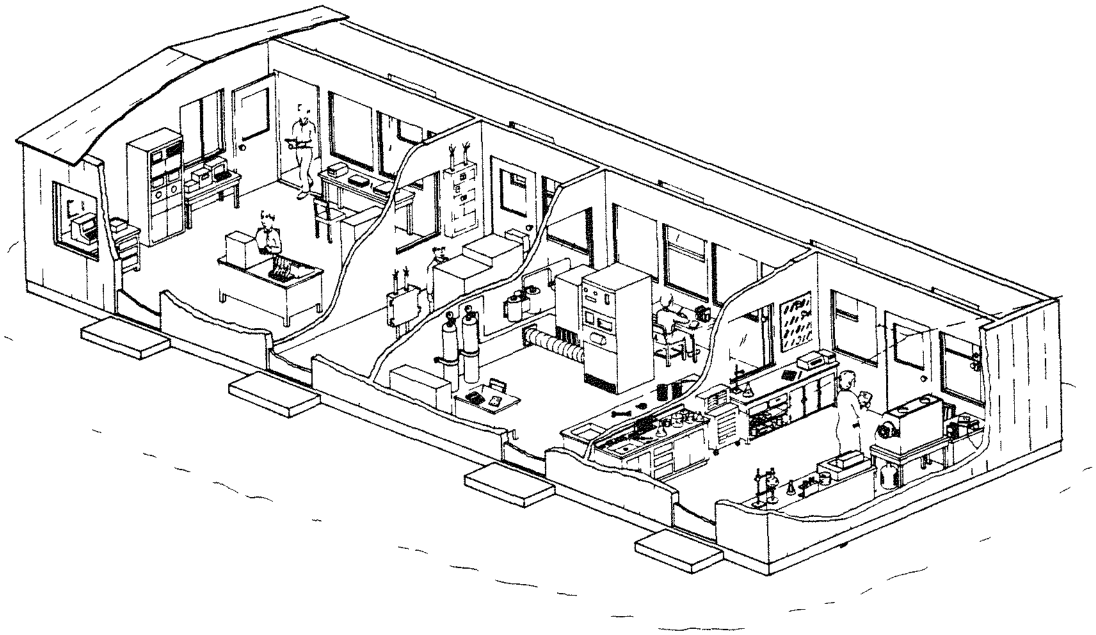

Figure 1-1. Cutaway View of HTEC Building

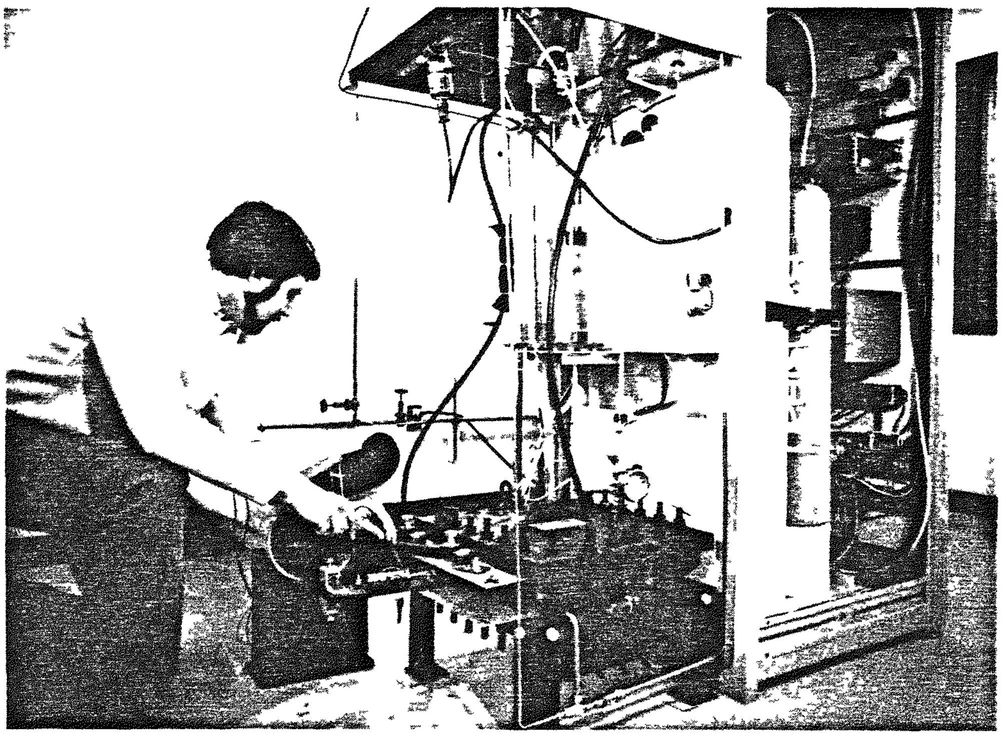

Figure 1-2. GE SPE Electrolyzer Module (bottom center) and Console (cover removed)

This compressor has now undergone both closed- and open-cycle testing at the BNL Hydrogen Technology Evaluation Center. The closed-cycle test program, conducted under a no-cost loan agreement between BNL and PSE&G (with technical assistance provided by Ergenics) involved development of a comprehensive map of compressor performance under laboratory conditions. A matrix of parametric tests were carried out at 80 different sets of input conditions. Bottled ultra-high purity hydrogen was used in a closed, recirculated system.

The open-cycle test program, conducted for EPRI under contract RP 1086-20, characterized compressor operation with input conditions closer to those of actual use, but with laboratory controls and measurement techniques. The BNL SPE electrolyzer provided hydrogen which was purified and then compressed. A restricted set of parametric tests were conducted, followed by a 5-day continuous test of compressor performance at optimal input conditions.

HOW THE METAL HYDRIDE COMPRESSOR WORKS

The metal hydride compressor is pictured in Figure 1-3 and is shown schematically in Figures 1-4 and 1-5. The compressor consists of two essentially identical circular beds, each containing four stages (Figure 1-5). These stages contain different compositions and weights of rare earth/nickel/iron/aluminum alloys and are designed for operation over different pressures ranges. The compressor is operated by alternately running hot and cold water through the water jackets surrounding each set of hydride beds. Hot water is obtained from two 120-gallon hot water heaters; cold water is obtained directly from the main water supply. The flow of water is controlled by electrically operated solenoid valves (as shown in Fig. 1-5).

When cold water is passed through bed A, the low temperature favors adsorption of hydrogen. At the same time, hot water is passed through bed B, where high temperature favors hydrogen desorption. As a result , hydrogen flows from stages 1, 2, and 3 in bed B to stages 2, 3, and 4 in bed A. During this time, hydrogen adsorbs onto stage 1 in bed A from the hydrogen inlet line and stage 4 in bed B desorbs hydrogen to the compressor outlet. After half of the compression cycle time, the hot and cold water flows are switched so that the stages in bed A now desorb while the stages in bed B adsorb hydrogen. A continuous flow of hydrogen is produced by this cycling of temperature in the two beds.

If the outlet water flows were switched at the same time as the inlet flows, during the time that hot water displaces the cold in one of the water jackets, cold water could enter the hot water loop. In similar fashion, a volume of hot water equal to

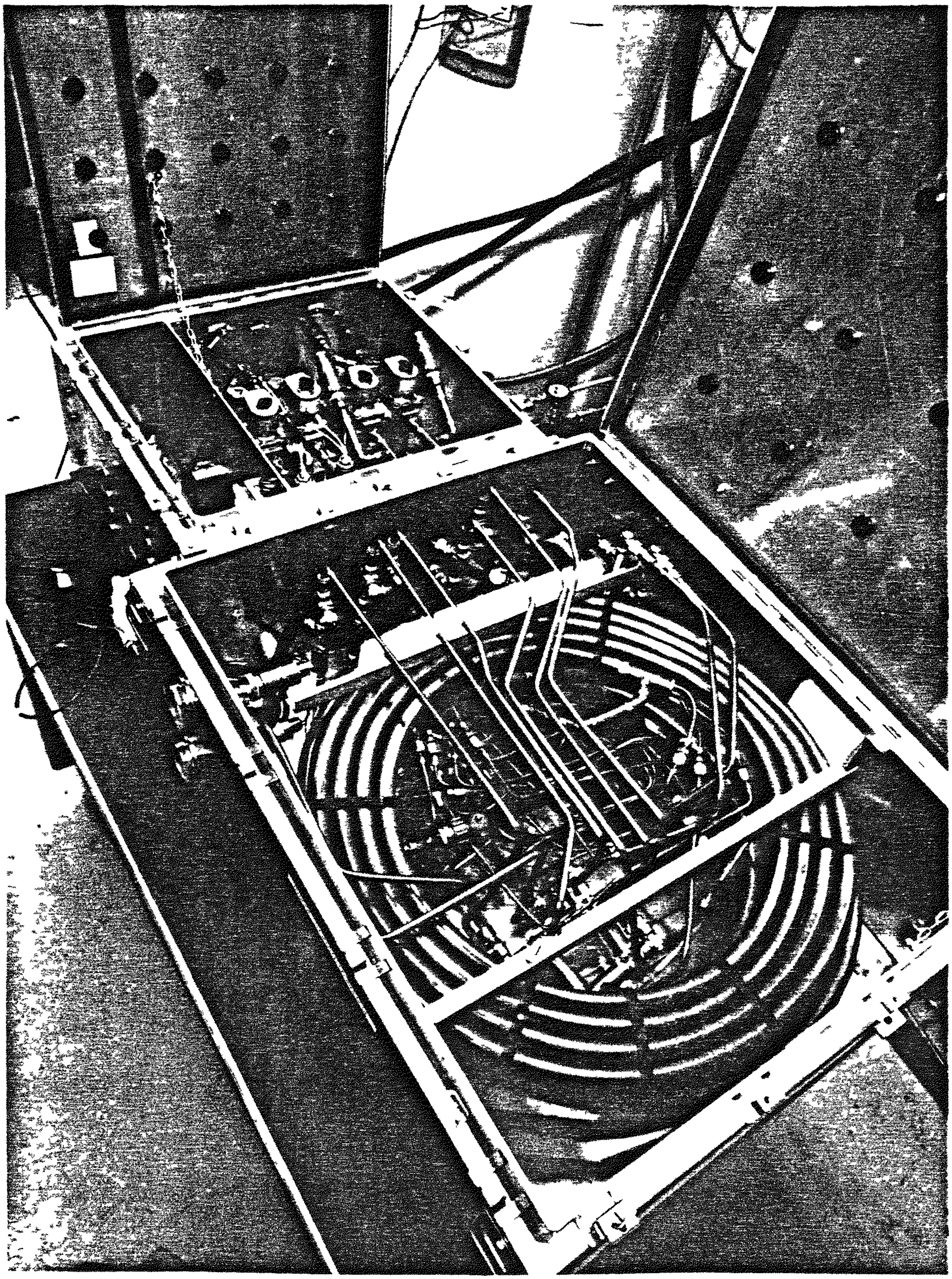

Figure 1-3. Ergenics 3 SCFM Heat-Actuated Metal Hydride Compressor

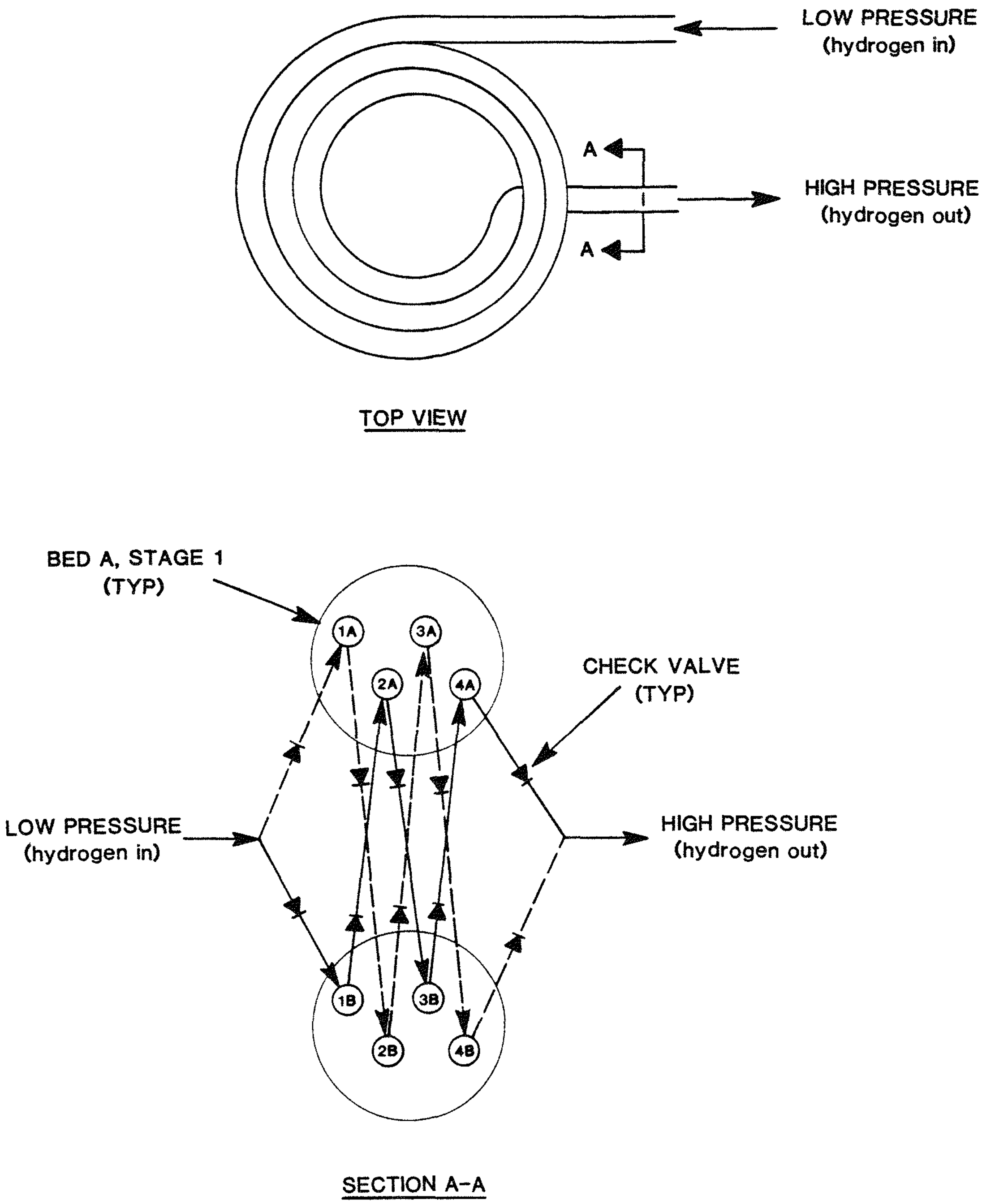

Figure 1-4. Schematic of a Two-Bed, Four-Stage Metal Hydride Compressor

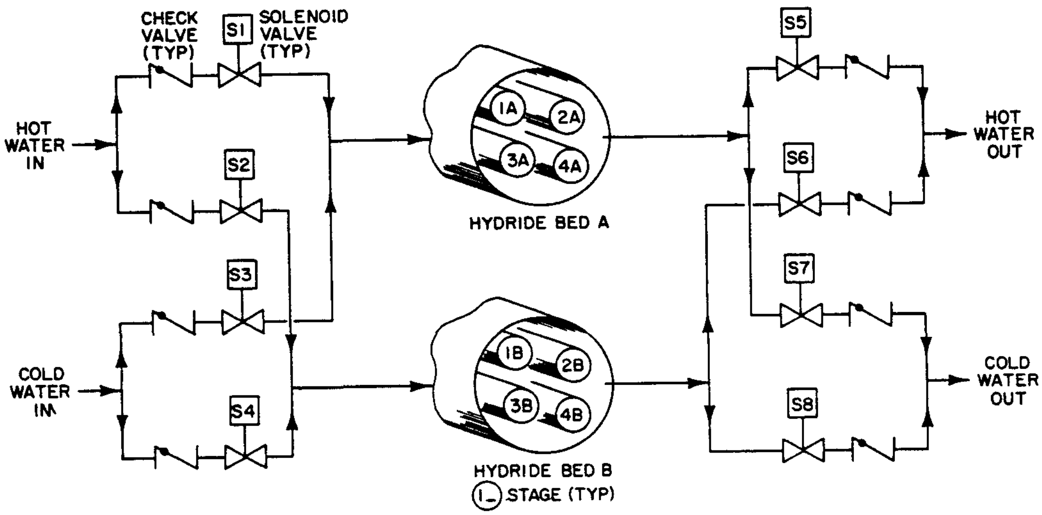

Figure 1-5. Four-Stage Metal Hydride Hydrogen Compressor Water Flows

the holdup in one water jacket would pass out to the drain. In order to prevent the loss of hot water that would occur if the outlet water flows were switched in this manner, a temperature-sensitive delay operates on the water outlet lines from the compressor. The delay prevents the switching of the outlet cold water flow to the hot water loop until the temperature of the stream is greater than 131°F.

THE WATER SYSTEM

The hot and cold water system is shown schematically in Figure 1-6. Hot water is provided to the compressor via a closed loop containing two 120-gallon 12 kW electric hot water heaters (shown in Figure 1-6) at temperatures up to 190°F (88°C). Water is circulated by a 1.5-hp centrifugal pump, although a 1/3-hp pump would be adequate.

Cold water is provided by a 1-pass system which contains one hot water heater for preheating, if desired. Both water flow rates are measured using target-type flow meters. Water temperatures are measured using type-T thermocouples.

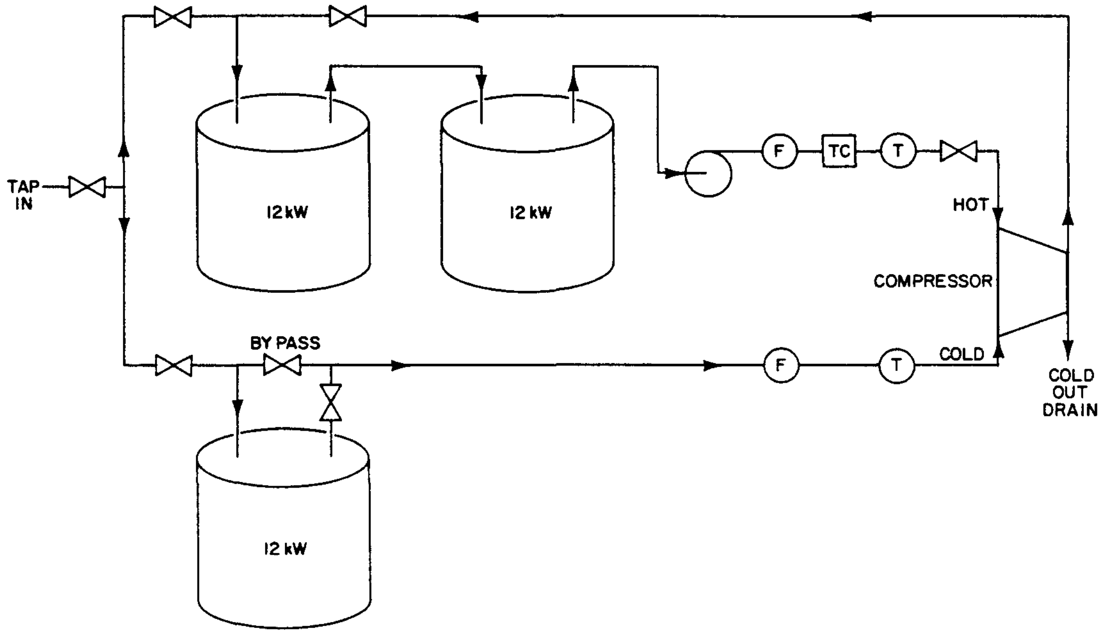

Figure 1-6. Schematic of Hot and Cold Water System

The hot water loop is pressurized and the cold water loop is vented to ambient. When the inlet solenoid valves are switched, the hot water is vented and the cold water is circulated to the hot water tank until the outlet solenoid valves are switched. When the hot and cold water flow rates were not equal, it was impossible to keep the hot water tanks filled, resulting in a decrease in hot water flow.

CHRONOLOGY OF OPERATION

Table 1-1 presents a brief chronology of compressor testing at the BNL HTEC facility. As the table shows, the test loop and the compressor each suffered on major malfunction, but otherwise performed reliably.

TABLE 1-1

CHRONOLOGY OF BNL HTEC METAL HYDRIDE COMPRESSOR TESTING

Date	Event
12/84	Metal hydride compressor installed at BNL.
1/85	Shakedown of closed loop metal hydride compressor test loop.
2/7/85	Closed cycle compressor testing initiated.
3/7/85	A leak in a valve stem in the test loop halted operation.
3/26/85	Closed cycle testing resumed.
4/11/85	Closed cycle testing completed.
4/29/85	Compressor malfunctioned during supplementary test. Manufacturer reported that failure was caused by inadvertent use of carbon steel instead of stainless steel heat exchanger plug. The compressor was regenerated at Ergernics.
7/85	Open cycle test loop was constructed.
8/85	Metal hydride compressor was reinstalled at BNL. Shakedown of open loop metal hydride compressor completed.
8/16-8/29/85	Parametric testing conducted.
9/10-9/15/85	Long-term testing conducted.

Section 2

CLOSED CYCLE COMPRESSOR TESTING

PURPOSE

The closed-cycle compressor tests had two objectives:

- o Characterize compressor performance at on- and off-design operating conditions.
- o Identify optimal operating conditions.

To characterize compressor performance, a matrix of 80 sets of test conditions was developed measuring the sensitivity of hydrogen throughput and efficiency to changes in hydrogen pressures, water flow rates and temperatures, and cycle time. The results comprise a comprehensive "performance map" of the compressor. The optimal operating conditions are those which maximize hydrogen flow, compressor efficiency for the desired pressure ratios.

TEST SYSTEM

Hydrogen Loop

The closed-cycle compressor test system is pictured in Figure 2-1 and shown schematically in Figure 2-2. After compression, hydrogen is stored in two high-pressure ballast cylinders, provided to minimize high-side pressure fluctuations. An adjustable pressure regulator reduces the gas pressure to the compressor inlet pressure for recompression.

Hydrogen flow rates are measured using heated-wire-type mass flow meters. Due to the wide range of hydrogen flowrates encountered (approximately 0 to 12 SCFM), 3 flowmeters with different ranges are used. Gas pressures are measured with pressure transducers plus redundant gauges. Hydrogen inlet and outlet temperatures are measured with type-T thermocouples.

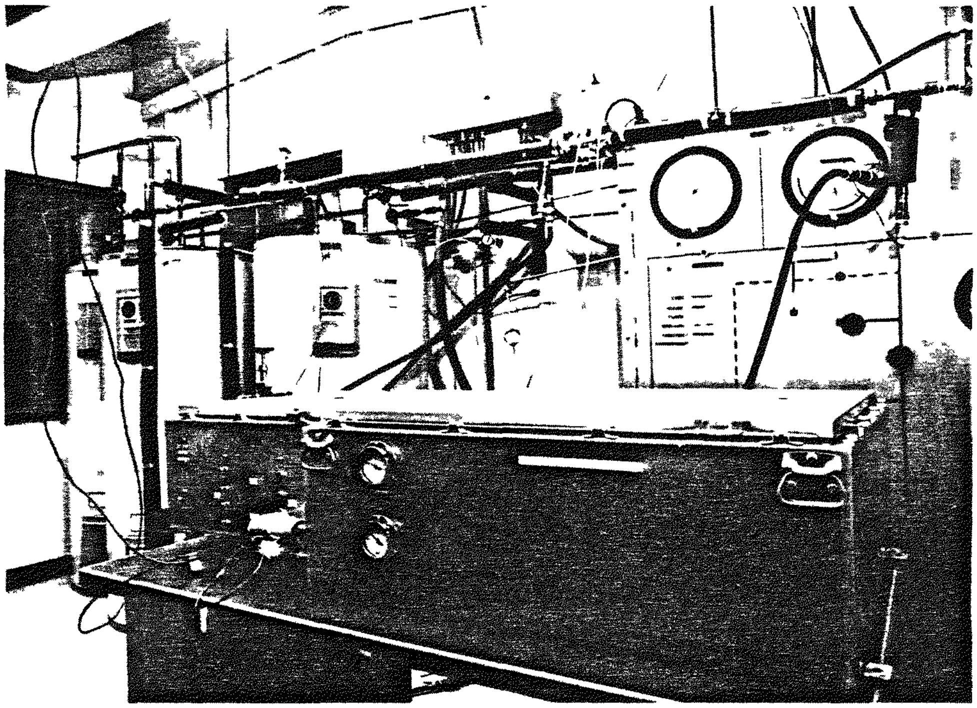

Figure 2-1. Heat-Actuated Metal Hydride Hydrogen Compressor (foreground) and Closed-Loop Compressor Test System

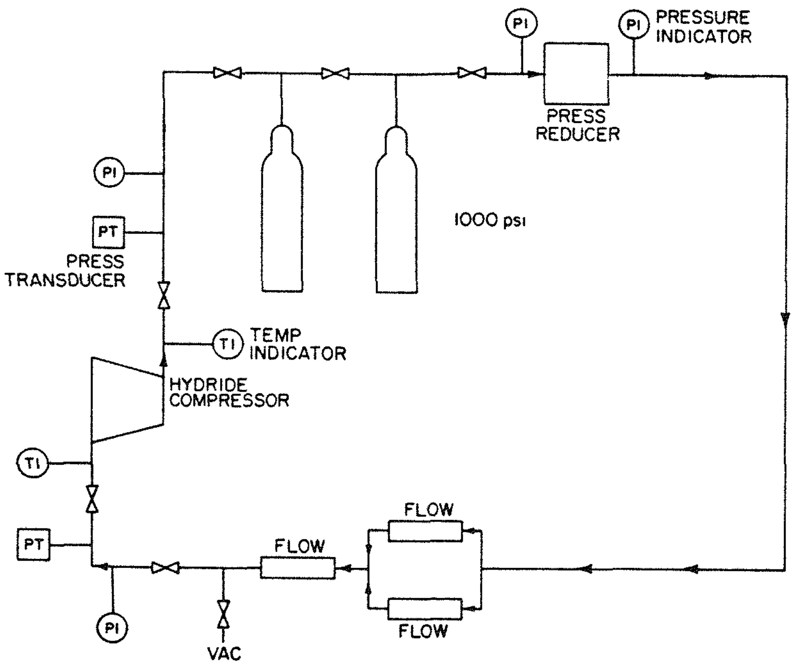

Figure 2-2. Schematic of Closed-Loop Compressor Test System

Data Acquisition Subsystem

A Fluke 2240B datalogger scans all sensors every 11 seconds and transmits the raw data to a Commodore 64 computer for conversion to engineering units, display, and disk storage. The computer also keeps running averages of hydrogen flow rate, water flows, compressor efficiency, and so on.

TEST PLAN AND METHODOLOGY

Test Conditions

In order to develop a compressor performance map, the efficiency and hydrogen flow rate of the compressor was evaluated at 80 different sets of input conditions. Table 2-1 presents the input parameter values used.

Table 2-1

INPUT PARAMETER VALUES

Input Parameter	Values
Hot water inlet temperature (°F)	150, 168, 185
Water flow rates (GPM)	3, 4, 5
Hydrogen inlet pressures (psia)	80, 100, 120
Hydrogen outlet pressures (psia)	800, 900, 1000
Cycle time (min)	2, 3, 4, 9

Inputs and Outputs

The quantities monitored by the datalogger every 11 sec. during each test are shown on Table 2-2. All quantities marked "I" are inputs and can be preset. All other measured quantities are marked "O" for output.

Test Procedure

To determine test duration, trial runs were made with randomly selected input conditions for five full cycles, ten full cycles, and twenty full cycles. It was found that the compressor reached steady operation within five full cycles; i.e., the average hydrogen flow rate varied less than 5% and the water temperatures varied less than 2%, when the number of cycles was increased from 5 to 10. Each test was conducted by changing one of the input parameters in Table 2-1 and allowing the compressor to cycle five times to reach steady operation before initiating the test. Data was then collected over ten full compressor cycles.

Table 2-2

CLOSED CYCLE COMPRESSOR TESTING MEASURED QUANTITIES

Quantity	Units	Input (I) or Output (O)
H_2 flow rate from 50,000 cc/min flow meter #1	[SCFM]	O
H_2 flow rate from 50,000 cc/min flow meter #2	[SCFM]	O
H_2 flow rate from 25 cfm flow meter	[SCFM]	O
Cold water flow rate	[GPM]	I
Hot water flow rate	[GPM]	I
Compressor inlet pressure	[PSIA]	I
Compressor outlet pressure	[PSIA]	I
Inlet hot water temperature	[°F]	I
Outlet hot water temperature	[°F]	O
Outlet H_2 temperature	[°F]	O
Inlet cold water temperature	[°F]	I
Outlet cold water temperature	[°F]	O
Inlet H_2 temperature	[°F]	O
Cycle time	[Min]	I

After the system was stabilized and all inputs were satisfactory, the compressor tests were conducted. Certain raw data and computed quantities were averaged over each test run:

Hydrogen flow
Hot water flow
Cold Water flow
Hot water temperature both in and out
Cold water temperature both in and out
Hydrogen temperature both in and out
Hydrogen pressure both in and out

Certain quantities were integrated over each test run:

The heat into the compressor from the hot water

The heat rejected by the compressor to the cold water

The work done compressing the gas

The heat gained by H_2

The efficiency of the compressor*

TEST RESULTS

Figures 2-3 through 2-11 present selected test results. Detailed test results are presented in Appendix B. Figures 2-3, 2-4, and 2-5 present hydrogen flow rate, compressor efficiency, and total hydrogen absorption versus cycle time at specific hot water inlet temperature, for typical absolute hydrogen pressures and water flow rates. Figure 2-3 shows hydrogen flow decreases steadily as cycle time increases from two to nine minutes, except at the highest temperature (183°F) where a broad maximum is found. Increasing the hot water temperature greatly increases hydrogen flow, e.g., for a two-minute cycle 3.3 SCFM (94 SLPM) at 183°F versus 2.3 SCFM (64 SLPM) at 168°F, and 1.3 SCFM (36 SLPM) at 150°F.

Figure 2-4 shows that compressor efficiency is greatly increased by increasing hot water temperature, and less so by increasing cycle time, until a 6-7 minute cycle is reached. The peak compressor efficiency observed is about 3%, which is quite low, compared to the theoretical Carnot efficiency of 22% at these temperatures.

Figure 2-5 indicates that the total hydrogen absorbed increases linearly with cycle time until a six-minute cycle time is reached. This is probably why compressor efficiency does not rise for longer cycles, i.e., the hydride beds are saturated and can store no more hydrogen. Total hydrogen absorption is a strong function of hot water temperature.

Figures 2-6 and 2-7 present hydrogen flow rate and compressor efficiency versus cycle time at specific water flow rates for fixed hydrogen pressures and water temperatures. As in Figure 2-3, hydrogen flow decreases as cycle time increases, except at the lowest water flow rate where the low water flow probably limits heat transfer. Increasing the water flow rate from 3 GPM to 4 GPM greatly improves throughput, whereas an increase in water flow rate to 5 GPM only slightly improves the hydrogen flow rate. Figure 2-7 shows compressor efficiency, like hydrogen flow

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*The compressor efficiency is defined as the ideal isothermal work done in compressing the gas divided by the heat lost by the hot water stream. See Appendix A.

rate, is greatly increased by increasing the water flow rate from 3 GPM to 4 GPM. Little improvement is observed by increasing the water flow rate to 5 GPM.

Figures 2-8 and 2-9 examine the effect of water flow rates and temperature on hydrogen throughput and compressor efficiency. Figure 2-8 shows that hydrogen flow increases with water flow rate until about 4 GPM. A small increase in inlet hot water temperature dramatically increases the hydrogen flow rate, e.g., for a water flow rate of 5 GPM, 1.3 SCFM (36 SLPM) at 150°F versus 2.8 SCFM (79 SLPM) at 168°F, and 3.6 SCFM (101 SLPM) at 185°F. Compressor efficiency is much less sensitive to water temperatures and flows, as Figure 2-9 indicates.

Figures 2-10 and 2-11 examine the influence of hydrogen outlet pressure on hydrogen flow rate and compressor efficiency. The compressor outlet pressure was determined by the fullness of the ballast tanks (Figure 2-2) because there was no regulator in the system. Figure 2-10 shows that hydrogen flow increases strongly as hydrogen outlet pressure decreases. The effect on compressor efficiency is quite similar, as Figure 2-11 indicates.

Taken together, the figures indicate hydrogen flow is maximized at about 3.6 SCFM (101 SLPM) for a cycle time of about two to three minutes, with an efficiency of 2-3%, using 183°F water at a rate of 4-5 GPM, and a 900 psi hydrogen outlet pressure. Assuming that throughput is the important consideration rather than efficiency, and the hydrogen outlet pressure is fixed, these are the approximate optimal operating conditions.

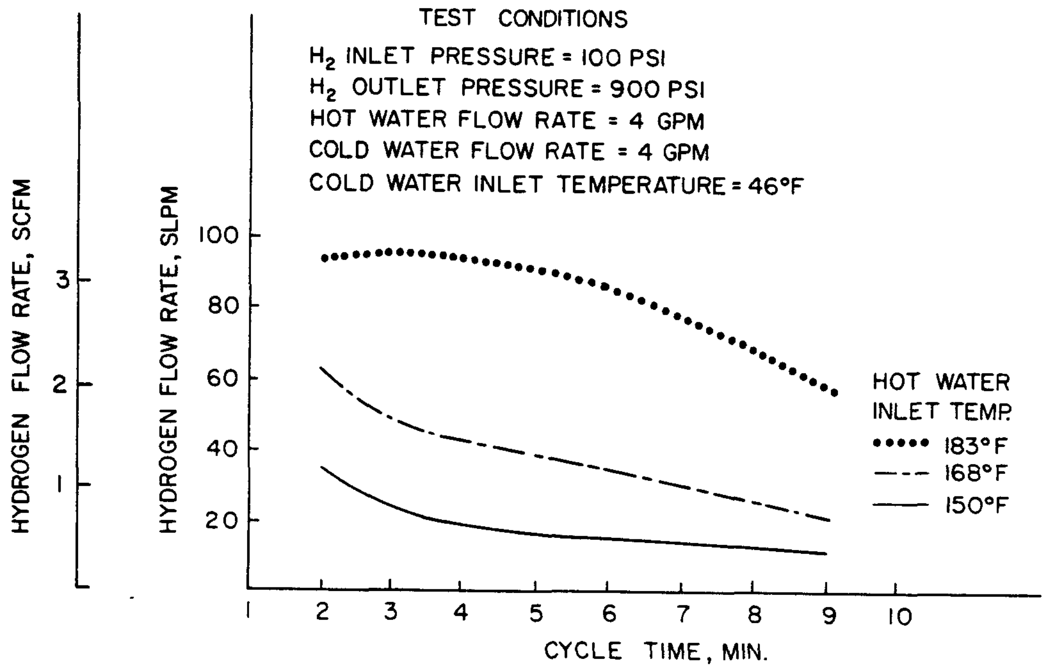

Figure 2-3. Hydrogen Flow Rate Versus Cycle Time and Hot Water Inlet Temperature

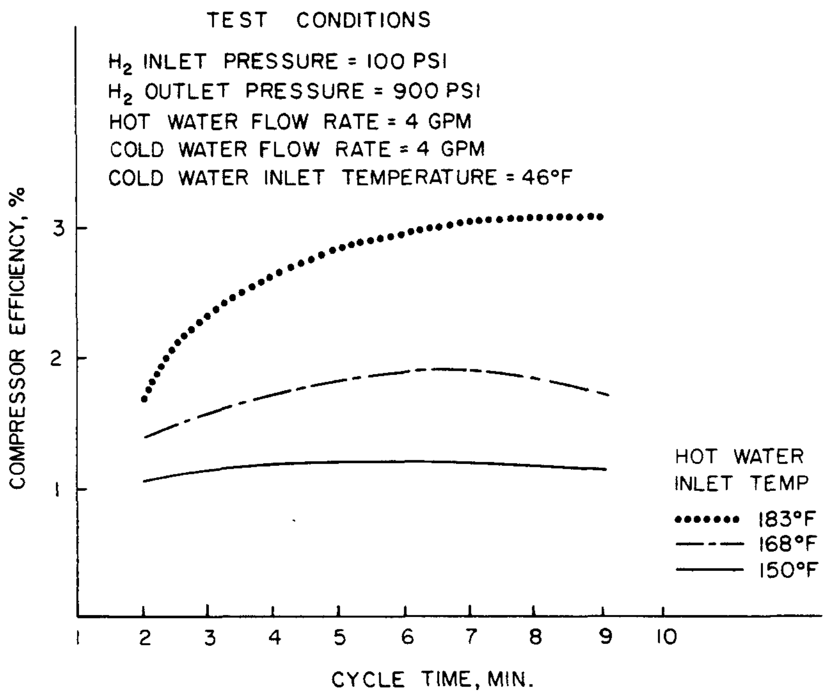

Figure 2-4. Compressor Efficiency Versus Cycle Time and Hot Water Inlet Temperature

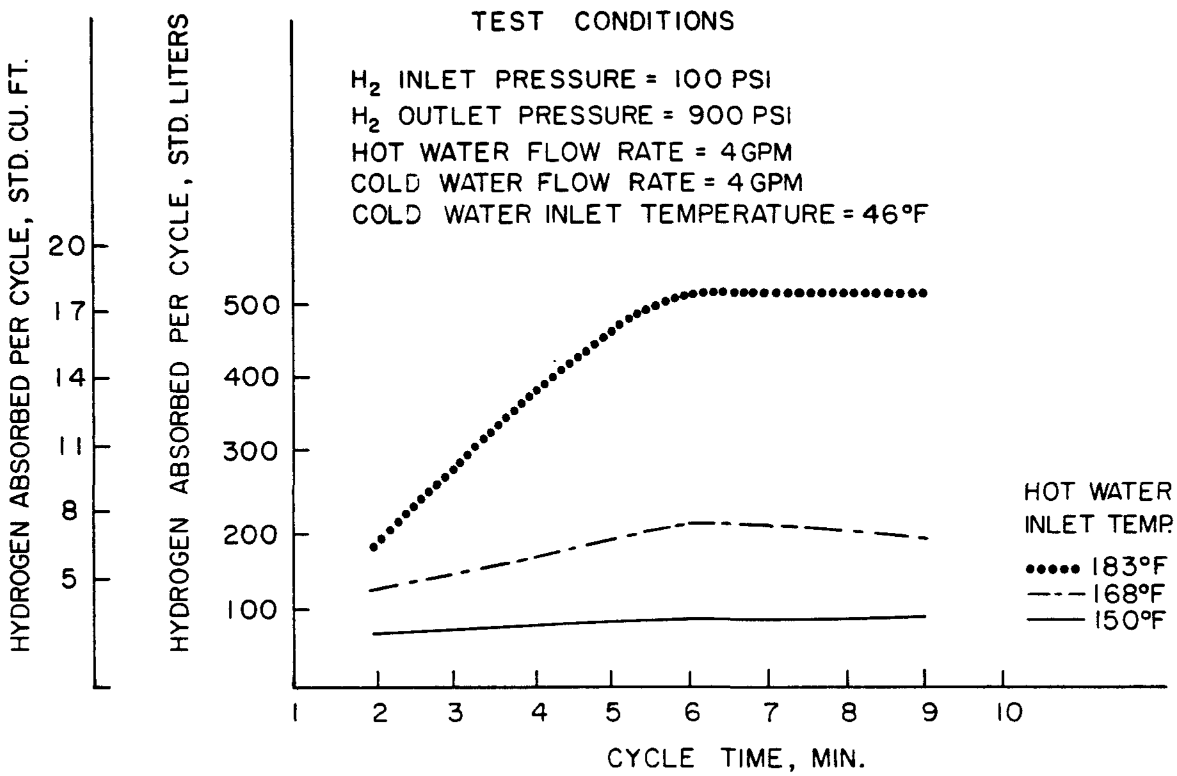

Figure 2-5. Hydrogen Absorbed per Cycle Versus Cycle Time and Hot Water Inlet Temperature

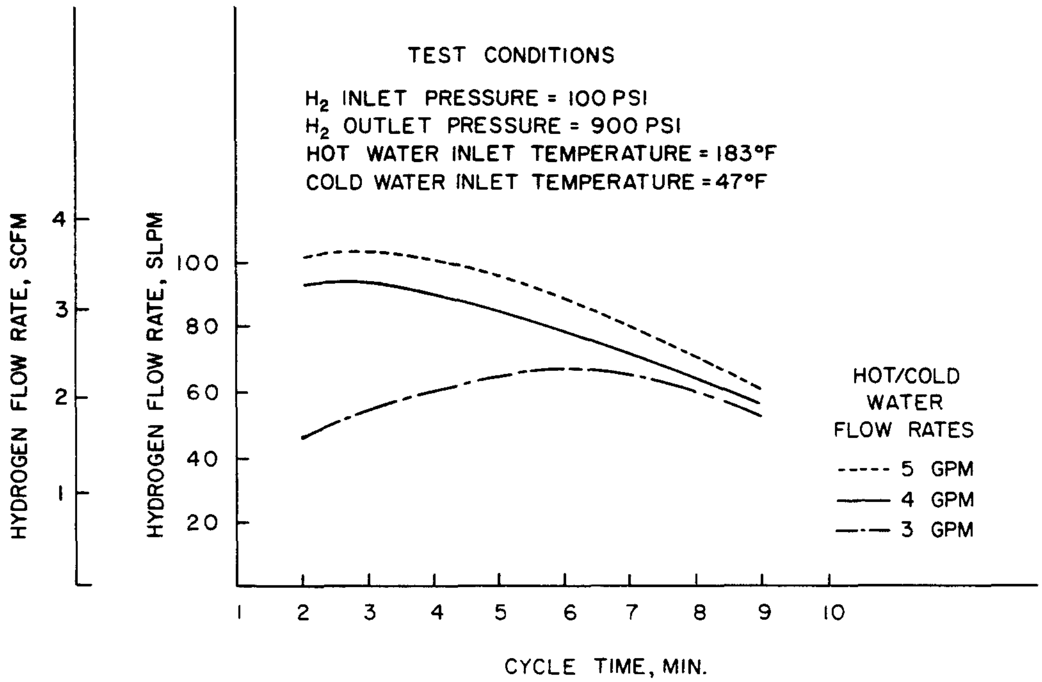

Figure 2-6. Hydrogen Flow Rate Versus Cycle Time and Hot/Cold Water Flow Rate

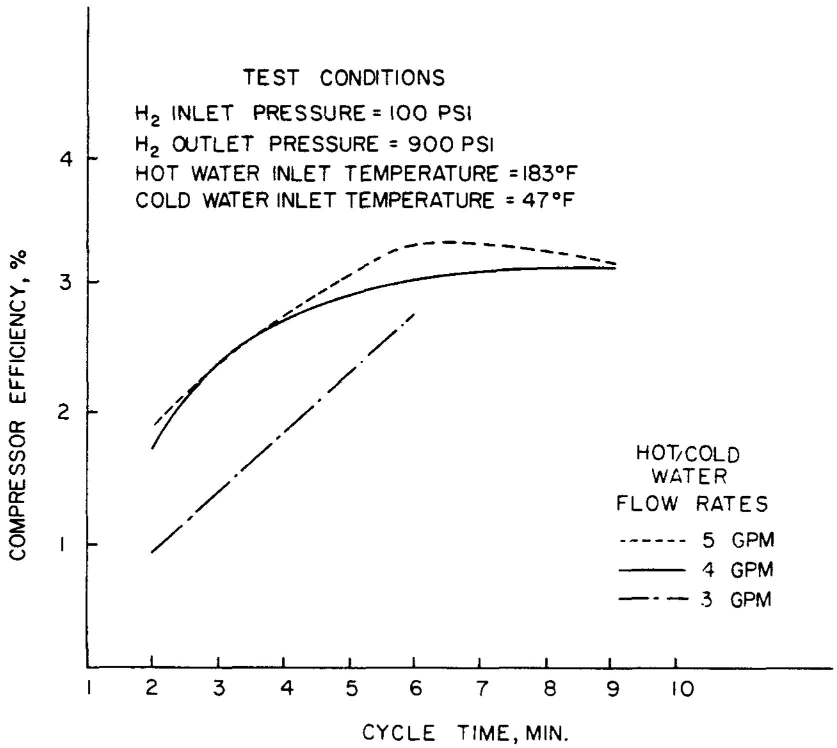

Figure 2-7. Compressor Efficiency Versus Cycle Time and Hot/Cold Water Flow Rate

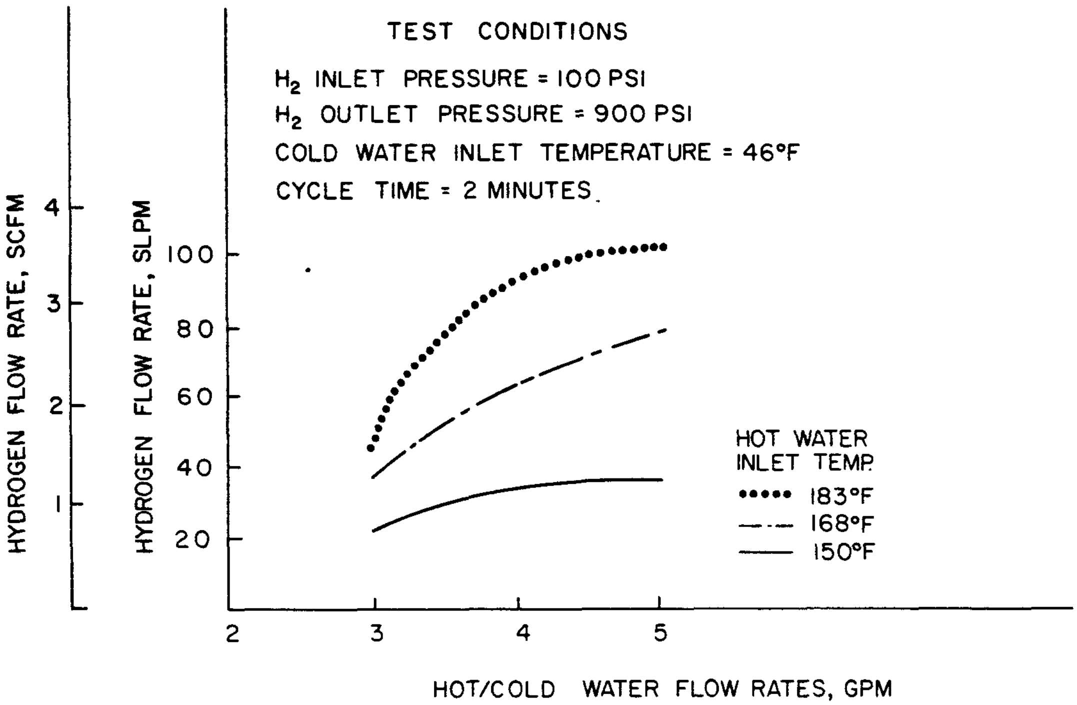

Figure 2-8. Hydrogen Flow Rate Versus Hot/Cold Water Flow Rate and Hot Water Inlet Temperature

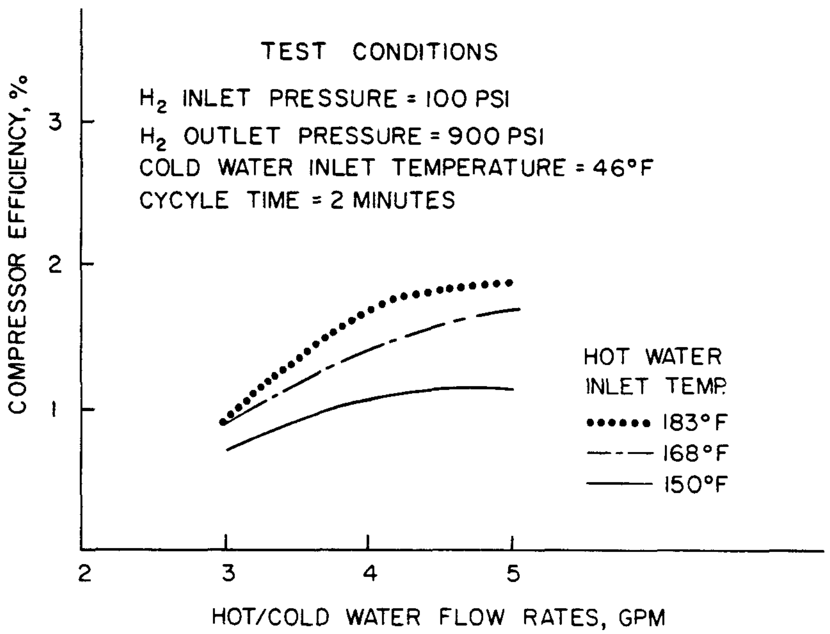

Figure 2-9. Compressor Efficiency Versus Hot/Cold Water Flow Rates and Hot Water Inlet Temperature

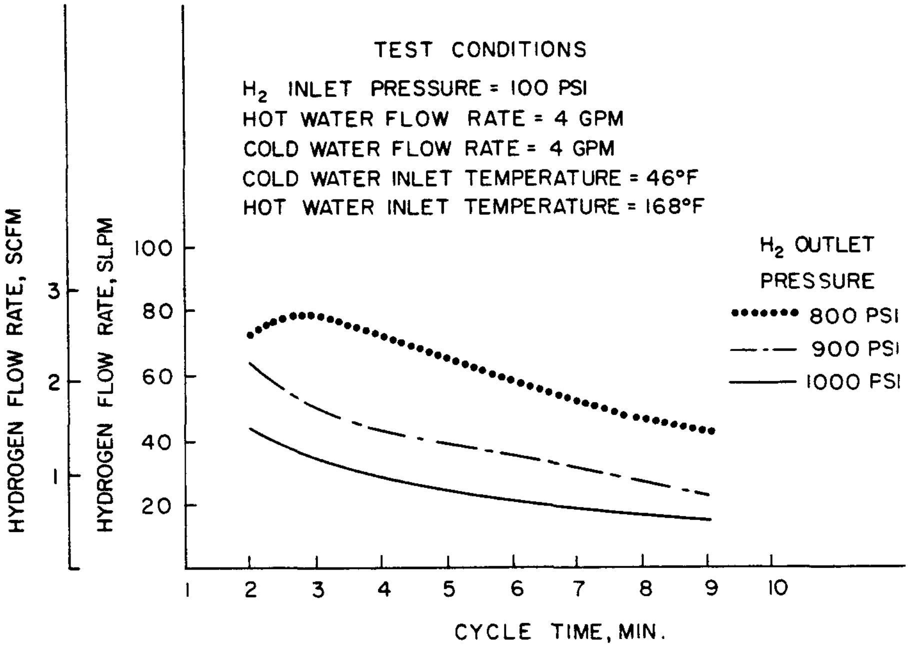

Figure 2-10. Hydrogen Flow Rate Versus Cycle Time and Hydrogen Outlet Pressure

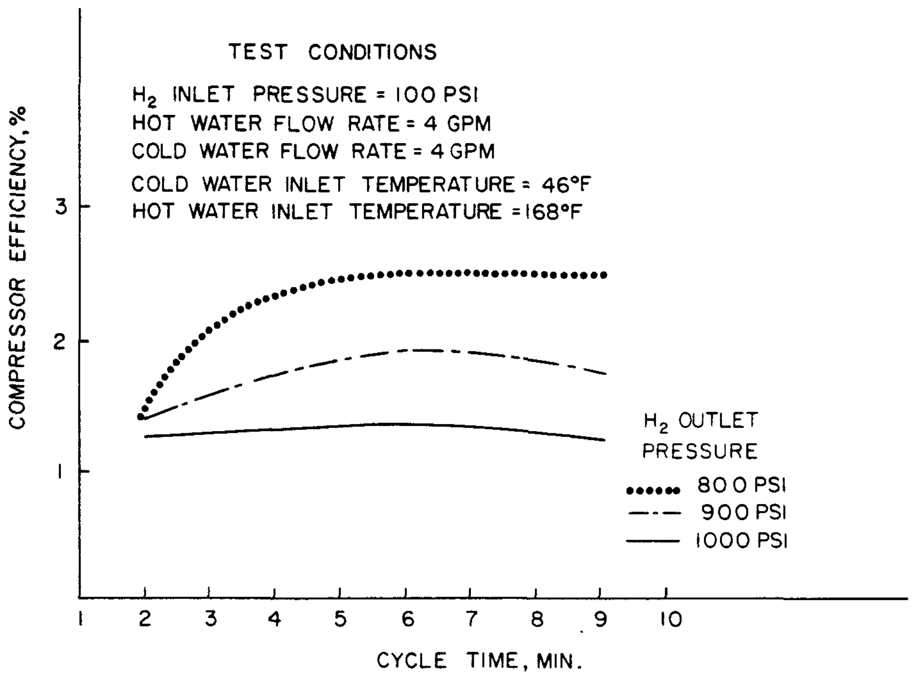

Figure 2-11. Compressor Efficiency Versus Cycle Time and Hydrogen Outlet Pressure

Section 3

OPEN CYCLE COMPRESSOR TESTING

PURPOSE

The purpose of these tests is to characterize the compressor--in terms of performance and any operational problems--using electrolytic hydrogen. A test system was built, including surge tanks and gas purification equipment, to interface the compressor with the BNL SPE electrolyzer system. This test system simulates the generator cooling system needs at PSE&G. The test program consisted of a small set of parametric tests based on closed-cycle test results, followed by a 5-day continuous test at optimal operating conditions.

THE OPEN CYCLE TEST SYSTEM

SPE Electrolyzer

Hydrogen was produced by the 8-cell 1 ft^2 cross-section Hamelton Standard SPE electrolyzer shown in Figure 1-2. Each cell consists of a fluoropolymer sheet which functions as the electrolyte for the process. The module can produce about 2 SCFM of hydrogen at its maximum power level of 15 kW. Electricity is provided by a computer-controlled power supply.

Due to the nature of the SPE module the water used for electrolysis must be kept very pure (resistivity above 4×10^6 ohm-cm). City water is passed first through a series of filters to remove dissolved organics and solid particles. Then it is processed in cation, anion, and mixed-column beds to remove ionic impurities. The water is kept clean by constant circulation through cation and mixed-column purification beds.

The hydrogen produced by the SPE module is saturated with water at roughly 85 to 160°F. Before leaving the SPE electrolyzer the hydrogen is dried to a dew point of roughly -4 to -40°F. About 10% of the hydrogen is vented with the water removed in the regenerative dryness.

The SPE electrolyzer is equipped with its own data acquisition/control subsystem which monitors and controls the SPE and its power supplies. Analog sensors which monitor temperatures, voltages, currents, flow rates, etc. are scanned approximately once every three seconds by a Fluke Model 2400-A "smart" datalogger. This device then digitizes and converts these data inputs to engineering units. The datalogger, under direction of a Fluke 1720-B Microcomputer, transmits control signals and alarms to the electrolyzer and its power supplies. Data, after being averaged and stored temporarily in the 1720-B computer, is downloaded hourly to the data acquisition/analysis computer, an IBM 9001, for permanent storage and analysis.

Hydrogen Loop

The open-cycle hydrogen loop is shown schematically in Figure 3-1. The SPE electrolyzer is located in the lower right-hand corner of this figure; the metal hydride compressor is on the extreme left-hand side.

Control valves direct hydrogen from the SPE electrolyzer either into the test loop or to a vent outside the facility. Check valves prevent the flow of high-pressure hydrogen or ambient air into the SPE electrolyzer.

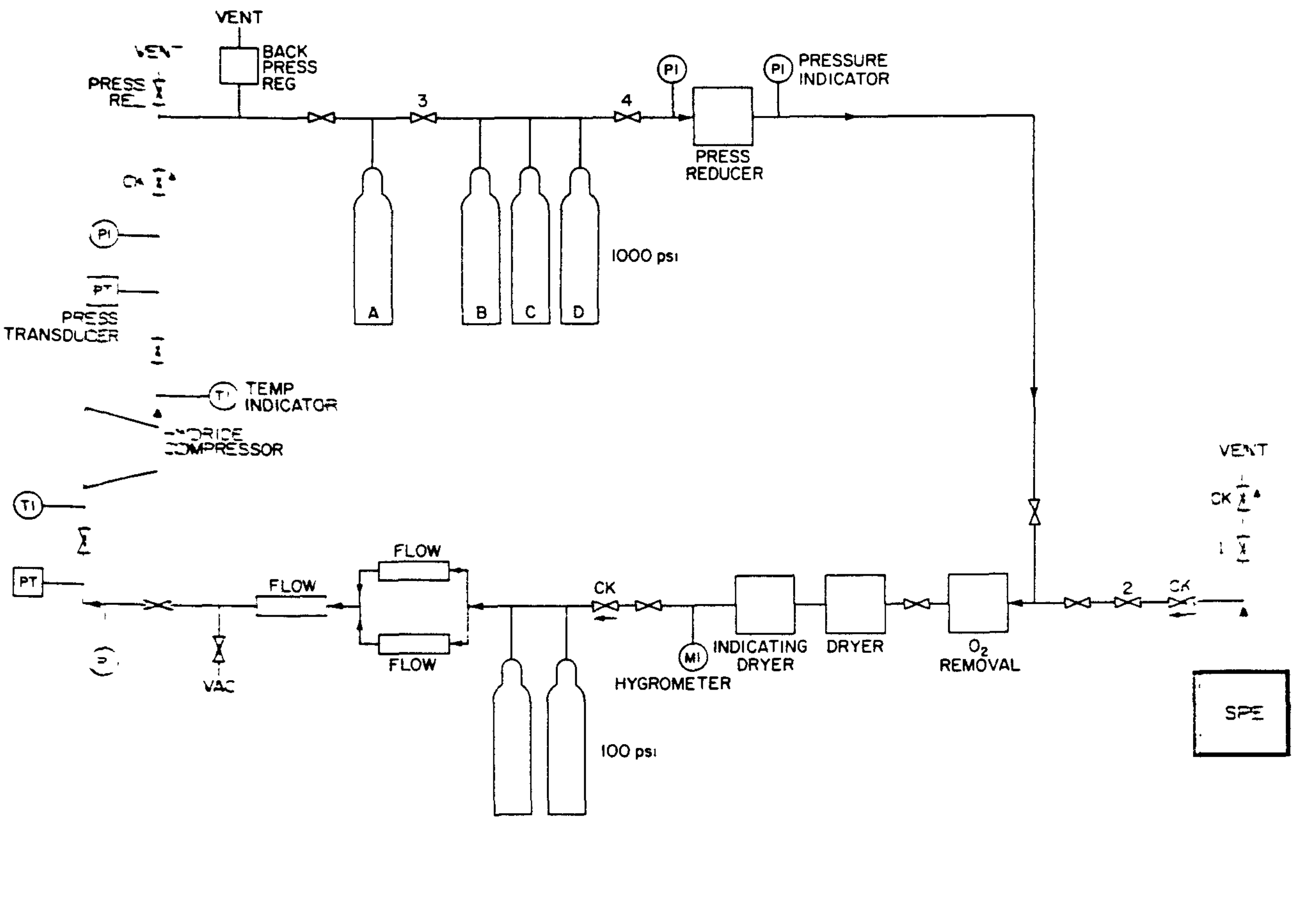

Figure 3-1. Schematic of Open Loop Compressor Test System

The metal hydride compressor requires extremely pure hydrogen (less than 1 ppm total impurities). Because the gas leaving the SPE has an impurity level of about 50 ppm--almost entirely oxygen and water--further purification is provided in the test loop. Oxygen is removed from the gas stream to less than 1 ppm (to produce water) via a catalytic hydrogen purifier, followed by a molecular sieve dryer to remove water to 1 ppm. A color change indicating dryer provides visual confirmation that the hydrogen has been adequately dried. The dew point of the gas entering the compressor averaged approximately -47°F (8 ppm) for the purametric tests, and -74°F (2 ppm) for the 5 day test according to the sensor used. However, the indicating dryer water outlet purity is claimed by the manufacturer to be higher (0.5 ppm).

The electrolyzer provides a constant hydrogen flow rate of about 1.7 SCFM at a nominal pressure of 115 psia. The compressor input, however, while averaging up to 3.0 SCFM, fluctuates from roughly 0.10 SCFM to about 7 SCFM during each compression cycle. Two surge tanks containing about 10 cubic feet of hydrogen each, are provided to maintain the hydrogen pressure between 95 and 135 psig despite this transient flow mismatch. This is necessary to prevent the electrolyzer from automatically shutting down due to excessive or inadequate hydrogen pressure.

On the outlet of the compressor an adjustable back-pressure regulator maintains hydrogen pressure at approximately 1000 psia. Excess gas is vented outside. A safety pressure relief valve is also provided. Four tanks provide hydrogen storage at roughly 1000 psia. This gas can be used to augment the hydrogen produced by the electrolyzer. As in the closed loop, an adjustable pressure regulator reduces the gas pressure to the compressor inlet pressure for recompression.

Test Loop Ancillaries

All sensors, the data acquisition system, and the water loop are as described in Section 2, except that a hygrometer has been added to the hydrogen loop to monitor hydrogen dryness. The test loop data acquisition system operates independently of the SPE electrolyzer data acquisition/control subsystem.

Test Loop Operating Modes

The open loop compressor test system shown in Figure 3-1 has four operating modes:

- Closed Loop Mode

In this mode, used to stabilize compressor system operation by running the compressor until the water temperatures, water flows, hydrogen pressures, and hydrogen flows are approximately constant, hydrogen is recirculated by the compressor as in the closed loop test system described in Section 2. This is accomplished by closing valve 2 (see Figure 3-1) and keeping all other valves open. During this mode the electrolyzer may be unused, or its gas may be vented by opening valve 1.

- Augmented One-Pass Mode

In this mode, used for short-term parametric tests, electrolytic hydrogen is augmented by gas from storage tanks B, C, and D shown in Figure 3-1. This is necessary because the electrolyzer output (about 2 SCFM) is not adequate to drive the compressor at its rated capacity (3 SCFM). These tanks provide enough hydrogen to operate at full compressor throughput for 4-6 hours.

In operation, valve 1 is closed and valve 2 is opened to divert electrolytic hydrogen into the loop where it combines with gas from tanks B, C, and D. This combined flow is purified, compressed, and then vented by the back-pressure regulator. Valve 3 is closed so that tank A, which contains 100 cubic feet, serves as a ballast to stabilize compressor outlet pressure as the hydrogen flow rate fluctuates from roughly 0.1 to 7.0 SCFM.

- Augmented Recycle Mode

In this recirculating mode, used for the 5-day continuous test, electrolytic hydrogen is augmented by gas from storage tanks A, B, C, and D. As in the previous mode, valve 1 is closed and valve 2 is opened to divert hydrogen from the SPE into the test loop. However, in this mode valve 3 is left open to permit some gas recycling (approximately 1 SCF). Most of the hydrogen (about 2 SCFM) is vented by the back-pressure regulator.

- Tank Filling Mode

After operation in the augmented one-pass mode, the electrolyzer is used to replenish tanks B, C, and D. This is done by closing valves 1 and 4, and opening valves 2 and 3. The SPE is then operated until the desired pressure is reached.

TEST PLAN AND METHODOLOGY

Parametric Test Conditions

Based on the closed cycle compressor performance map developed by evaluating 83 sets of input conditions, a set of input variables was determined for the open cycle compressor test. Table 3-1 presents the input parameter values used.

Table 3-1

PARAMETRIC TEST CONDITIONS

Input	Value	Rationale
Hot Water Inlet Temperature	1. 185°F/(85°C)	Max. available
Cold Water Inlet Temperature	1. Approx 55°F/(13°C)	Min. available
Hot/Cold Water Flow Rates	4 GPM 3 GPM	Optimal Minimum flow
Cycle Time	3 minutes 5 minutes	Maximum hydrogen flow Minimum hydrogen flow
H_2 Inlet Pressure	115 psia	PSE&G compressor specification
H_2 Outlet Pressure	1015 psia	PSE&G compressor specification

Parametric Test Procedure

In order to ensure that the system had reached steady operating conditions, it was operated in the closed-loop mode, while the gas produced by the electrolyzer was vented, for at least five full compressor cycles. Each test was conducted for four hours in the augmented one-pass mode. Two tests were conducted at each set of conditions in Table 3-1. Additional tests were conducted at other operating conditions as tabulated in Appendix A.

Long-Term Test

A continuous long-term test was conducted for five days at the optimal (in terms of hydrogen throughput) operating conditions given in Table 3-2. The system was operated in the augmented recycle mode at maximum electrolyzer hydrogen output of 1.7 SCFM (48 SLPM).

Inputs and Outputs

For both the parametric and long-term tests, the compressor-related monitored quantities are as described in Section 2. In addition, certain quantities were monitored by the SPE data acquisition/control subsystem, as presented in Table 3-3.

Table 3-2

LONG-TERM TEST CONDITIONS

Input	Value	Rationale
Hot Water Temperature	189°F	Max. available
Cold Water Temperature	57°F	Min. available
Hot/Cold Water Flow Rates	5.2 GPM	Max. available
Cycle Time	3 minutes	Maximum flow
H_2 Inlet Pressure	103 psia	Rated pressure
H_2 Outlet Pressure	1024 psia	PSE&G compressor specification

Table 3-3

SPE ELECTROLYZER MEASURED QUANTITIES

Quantity	Units
Module Current	[A]
Module Voltage	[V]
Module Temperature	[F°]
Hydrogen Flow Rate	[SCFM]
Hydrogen Pressure	[psia]
Hydrogen Dew Point (entering compressor)	[F°]

TEST RESULTS

Parametric Test Results

The parametric test results are displayed graphically in Figures 3-2, 3-3, and 3-4. Results are presented in more detail in Appendix C.

Figures 3-2 and 3-3 present hydrogen flow rate and compressor efficiency versus compressor cycle time and water flow rate. As for the closed loop tests (see Section 2), a cycle time of 2-3 minutes maximizes hydrogen throughput (see also

Appendix B). Hydrogen throughput and compressor efficiency both increase with water flow rate. As cycle time is increased from three to five minutes hydrogen throughput falls, but compressor efficiency rises, consistent with the closed cycle results.

Hydrogen flow rate and compressor efficiency are presented as a function of outlet hydrogen pressure in Figure 3-4. As the outlet pressure is increased both the flow rate and efficiency decrease.

Long-Term Test Results

Figure 3-5 presents the 5-hour average values of hydrogen flow rate, hydrogen outlet pressure and compressor efficiency vs. time. The shaded area of this figure is regraphed using hourly averages in Figure 3-6. As Figure 3-5 shows, during the 5-day period, the outlet pressure slightly increased, while the hydrogen flow and the compressor efficiency decreased.

Table 3-4 summarizes the long-term test results. Although test conditions closely paralleled purchase specifications, the hydrogen flow rate was 2.6 SCFM, 14% below the design flow rate of 3.0 SCFM. Compressor efficiency averaged 2.1%.

The reason for the slight pressure increase observed over the test periods is not clear. Possibly an increase in ambient temperature raised the pressure of the ballast cylinders which are kept outdoors. Alternatively, a small change in the backpressure regulator employed to vent the gas may have occurred.

The decrease in hydrogen flow and compressor efficiency over the 5-day test period is more noticeable. A possible explanation for this trend is hydride poisoning due to inadequate hydrogen purification. However, the catalytic purifier is designed to reduce the oxygen content to less than 1 ppm. while the 2 dryers should reduce the water content to less than 0.5 ppm.

Assuming 1 ppm each of water and oxygen, the total impurities introduced to the hydride beds during the test totals only about 0.02 SCF, i.e., roughly 0.1% of the beds' capacity of 20 SCF (see Figure 2-7). Even if the level of impurities was 10 times greater (5 times the dewpoint sensor reading), the effect on the hydride beds would be much less than the observed hydrogen flow rate degradation. Thus, hydride poisoning due to inadequate gas purification is not likely to have caused the flow decline. The reason for the flow decline--aside from the pressure increase--is not understood.

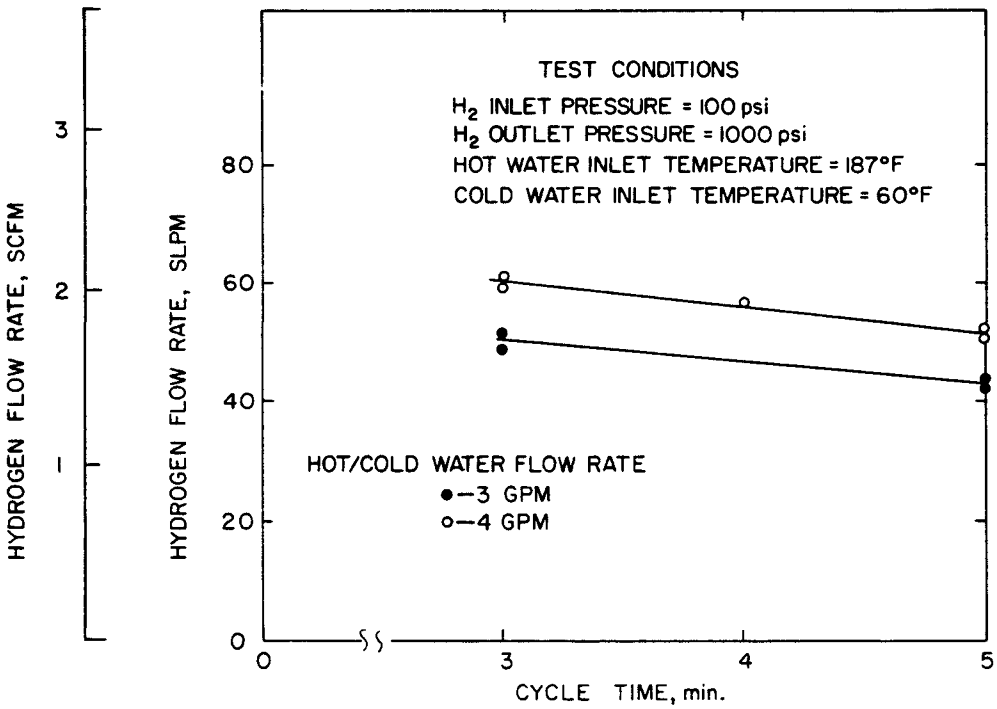

Figure 3-2. Hydrogen Flow Rate Versus Water Flow Rate and Cycle Time

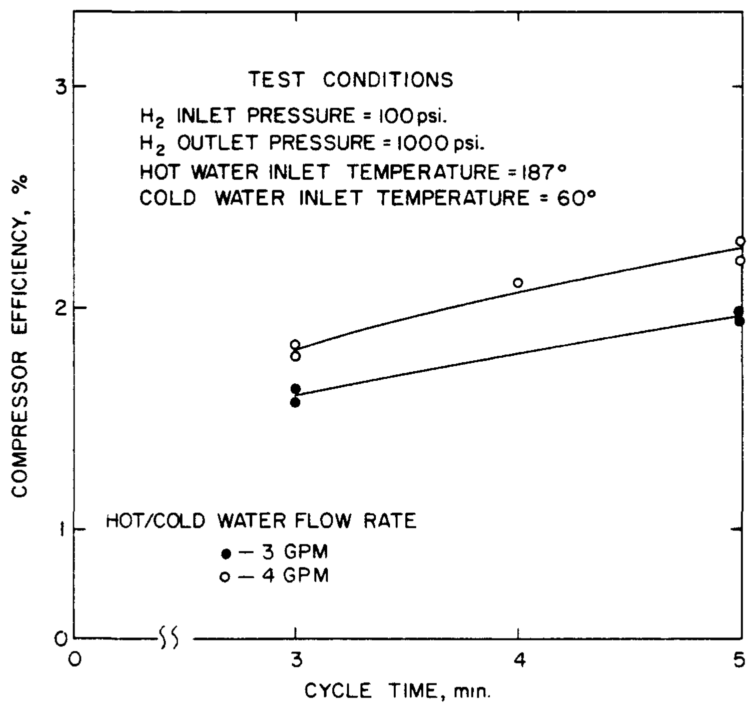

Figure 3-3. Compressor Efficiency Versus Water Flow Rate and Cycle Time

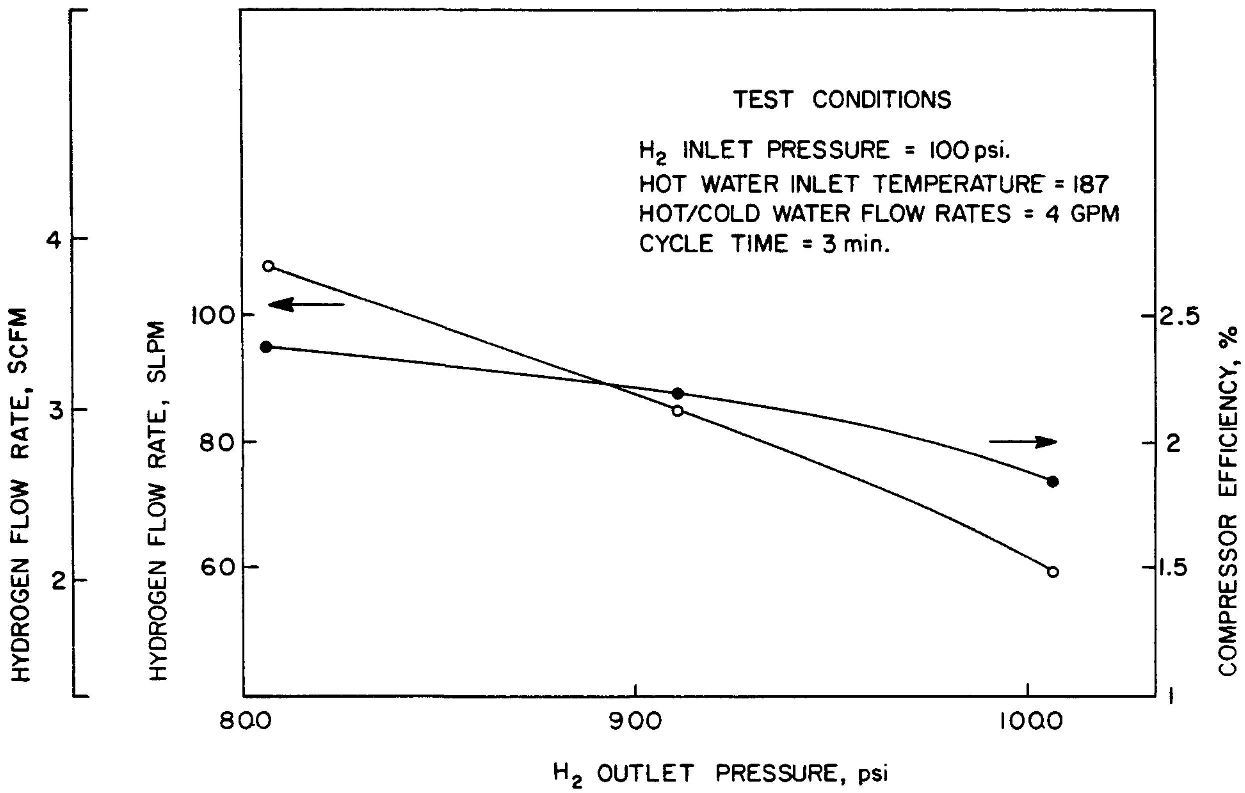

Figure 3-4. Hydrogen Flow Rate and Compressor Efficiency Versus Hydrogen Outlet Pressure

Table 3-4

LONG-TERM TEST RESULTS

Quantity	Purchase Specifications	Average Test Value
Hot Water Inlet Temperature	185°F	189°F
Hot Water Outlet Temperature	-	169°F
Cold Water Inlet Temperature	77°F	56°F
Cold Water Outlet Temperature	-	74°F
Hydrogen Inlet Pressure	115 psia	103 psia
Hydrogen Outlet Pressure	1015 psia	1029 psia
Hydrogen Flow Rate	3 SCFM	2.6 SCFM
Compressor Efficiency	-	2.1%*
Dew Point		-74°F (2 ppm)

*The compressor efficiency is defined as the ideal isothermal work done in compressing the gas divided by heat lost in the hot water stream.

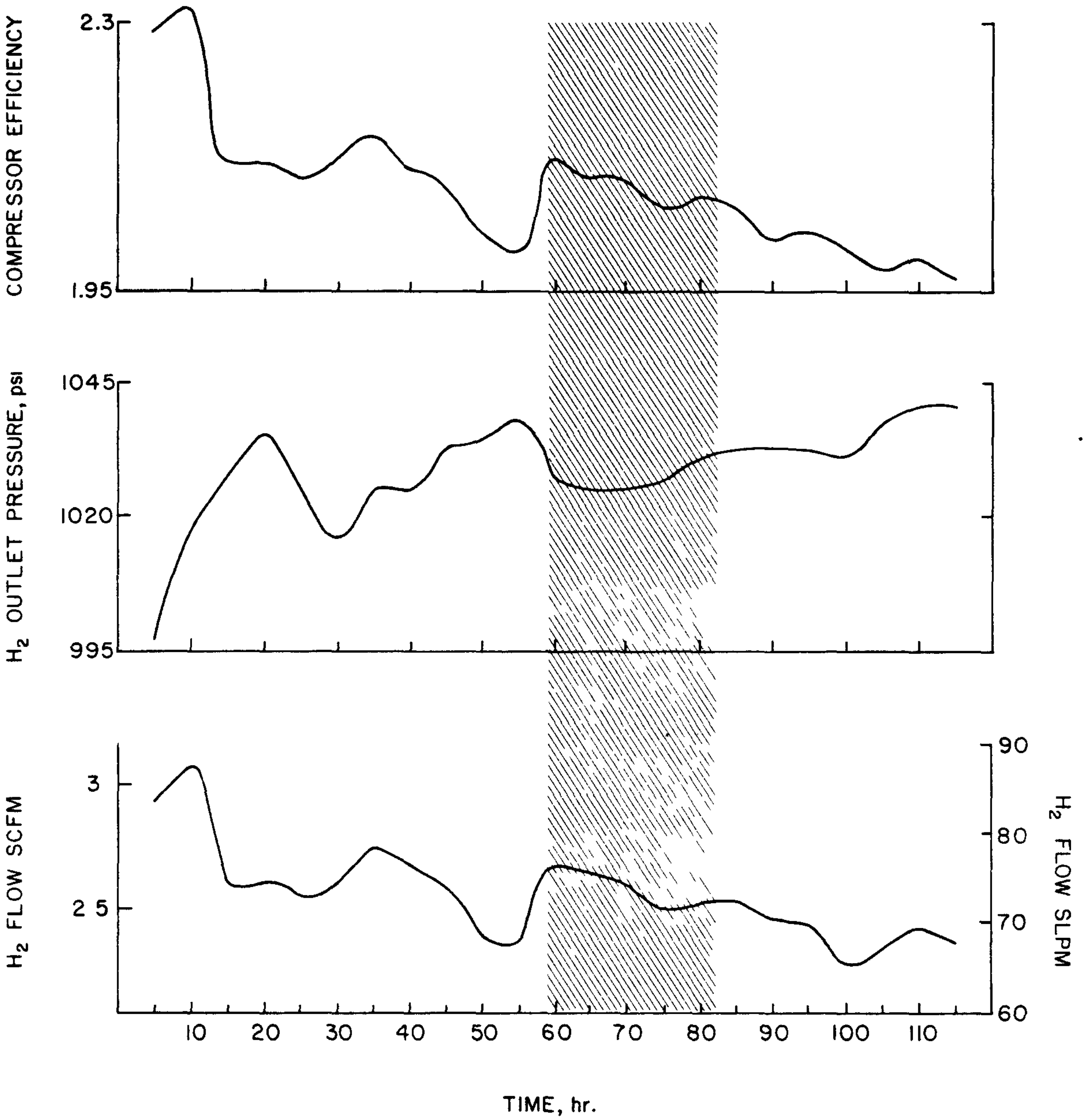

Figure 3-5. 5-Hour Average Hydrogen Flow Rate, Hydrogen Outlet Pressure and Compressor Efficiency Versus Time

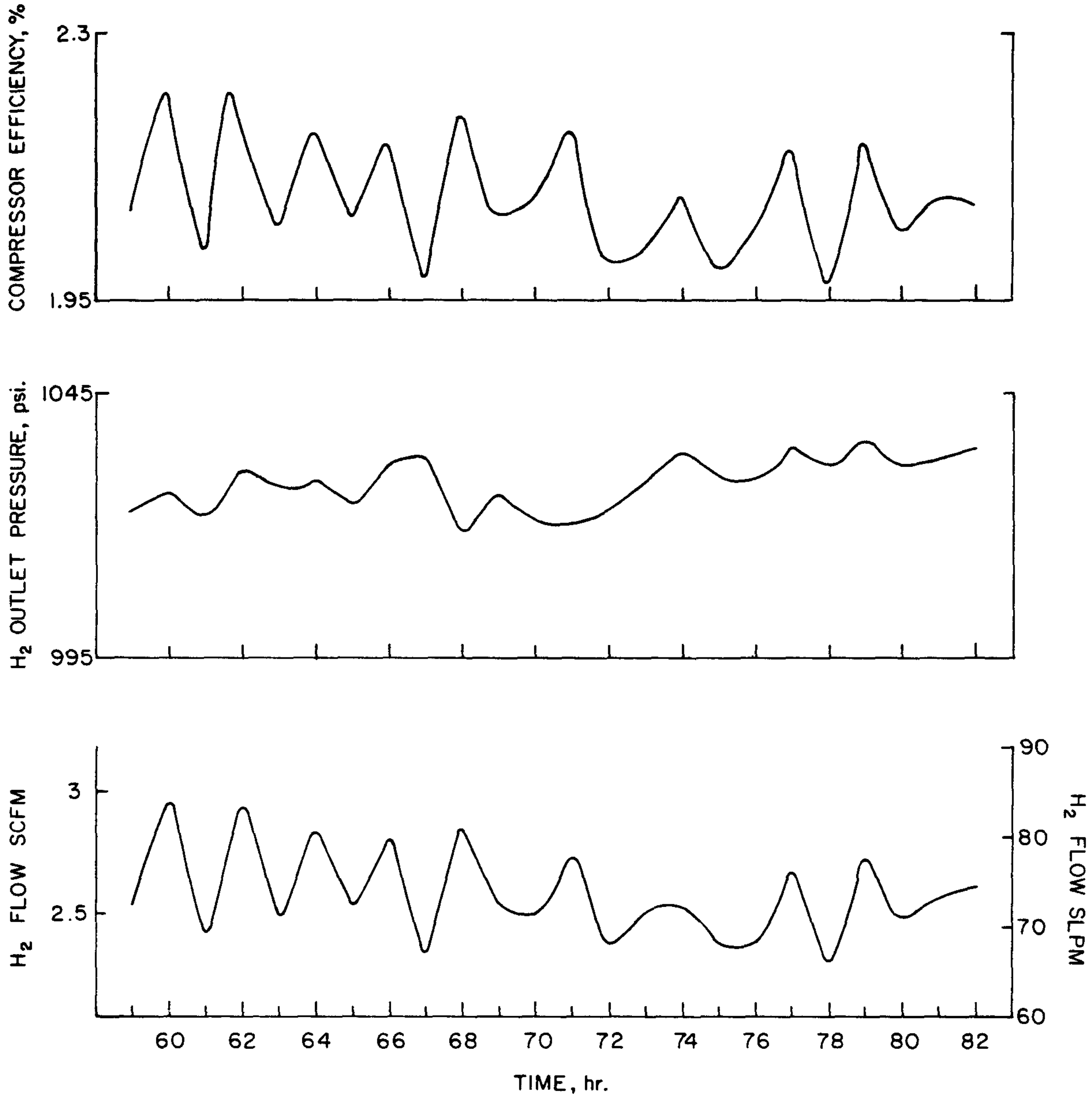

Figure 3-6. Hourly Average, Hydrogen Flow Rate, Hydrogen Pressure, and Compressor Efficiency Versus Time

Figure 3-6 examines the short-term fluctuations in hydrogen flow and compressor efficiency during a segment of the long-term test. The hydrogen throughput frequently varies 5-10% above or below the mean value. Compressor efficiency and hydrogen flow fluctuations appear to be strongly correlated. Due to the temperature band in the controller used to regulate the hot water temperature, the average hot inlet water temperature varied from 188°F to 192°F. There seems to be a direct correlation between hot water inlet temperature and hydrogen flow rate.

Section 4

COST/BENEFIT ANALYSIS

COMPRESSOR COST/PERFORMANCE ASSUMPTIONS

This section presents a simple economic comparison of metal hydride versus mechanical hydrogen compression. Table 4-1 presents the cost and performance data used in the analysis, obtained from discussions with manufacturers of each type of compressor. As Table 4-1 indicates, the mechanical compressor has higher capital and O&M costs, but also a much higher efficiency and hence lower energy consumption. Both compressors are expected to have comparable lifetimes, given proper maintenance.

Table 4-1

COMPRESSOR COST AND PERFORMANCE ASSUMPTIONS

Parameter	Compressor Type: Mechanical[1]	Compressor Type: Metal Hydride[2]
Throughput (SCFM)	3	3
Input Pressure (psi)	100	100
Output Pressure (psi)	1000	1000
Capital Cost ($)	22,000	9000
Annual Operating and Maintenance Expected (% of Capital Cost)	6	2
Lifetime (Years)	20	20
Salvage Value ($)	0	0
Efficiency (%)	40 (electricity)	2.1 (85°C hot water)

[1]Conversation with Kevin Lewis of Pressure Products, Inc. (10/85)

[2]Conversation with Matt Rosso of Ergenics, Inc. (10/85)

COMPARISON APPROACH

The economic figure of merit used to compare the two compressor types is the annualized cost to compress each unit of hydrogen. A real discount rate of 6.1% is used. Property taxes, income taxes, and inflation are not considered in the analysis.

The annual hydrogen throughput, H(SCF/Yr), is given by

$$H = C_1 U$$

where C_1 = constant (1.58 x 10^6 SCF/Yr), the total throughput at 100% utilization and 3 SCFM; and U = compressor utilization (assumed to be 0.5 or 0.9), the fraction of time the compressor operates.

The annual cost for energy purchased to compress this hydrogen, E_{purch} (\$/Yr),

$$E_{purch} = \frac{RHC_2}{F}$$

where R = energy rate (\$/kWh); H is defined above; F = compressor efficiency (0.6 for mechanical and 0.021 for metal hydride); and C_2 = conversion constant (1.88 x 10^{-3} kWh/SCF), the theoretical isothermal work done to compress each SCF of hydrogen.

The annual cost for operation and maintenance, $E_{O\&M}$ (\$/Yr):

$$E_{O\&M} = C_c Q$$

where C_c = compressor capital cost (\$); and Q = annual O&M expense rate (0.06 for mechanical and 0.02 for metal hydride).

Thus, the total annual net cash outflow to operate the compressor, P (\$/Yr), is given by

$$P = E_{purch} + E_{O\&M}$$

The net present value of all capital and operating costs, NPV ($), is

$$NPV = C_c + F_a P$$

where C_c = compressor capital cost ($); P is defined above; F_a = present value of annuity factor (11.3777) $[1 - (1 + i)^{-n}]/i$ where i = annual discount rate (6.1%), n = system lifetime (20 years).

The annualized cost to compress hydrogen, A ($/SCF), is then given by

$$A = \frac{NPV}{HF_a}$$

RESULTS

Figure 4-1 presents the results of the economic comparison of mechanical versus metal hydride compressors. Results are given for two levels of compressor utilization, 0.5 and 0.9. Note that since the compressors use different energy sources--electricity for the mechanical unit versus heat for the metal hydride device--comparisons at equal energy costs are not generally meaningful. Instead, compression costs must be based on the expected energy cost for each type of unit.

As Figure 4-1 shows, the cost of compression is significantly reduced for both compressors by increased utilization. The metal hydride compressor, due to its lower capital cost and O&M expense compresses hydrogen at lower annualized cost for low energy prices. However, due to its low efficiency, the cost of compression of the hydride compressor is very sensitive to energy cost. Compression costs for the mechanical compressor, on the other hand, are quite insensitive to energy cost because of its far higher efficiency.

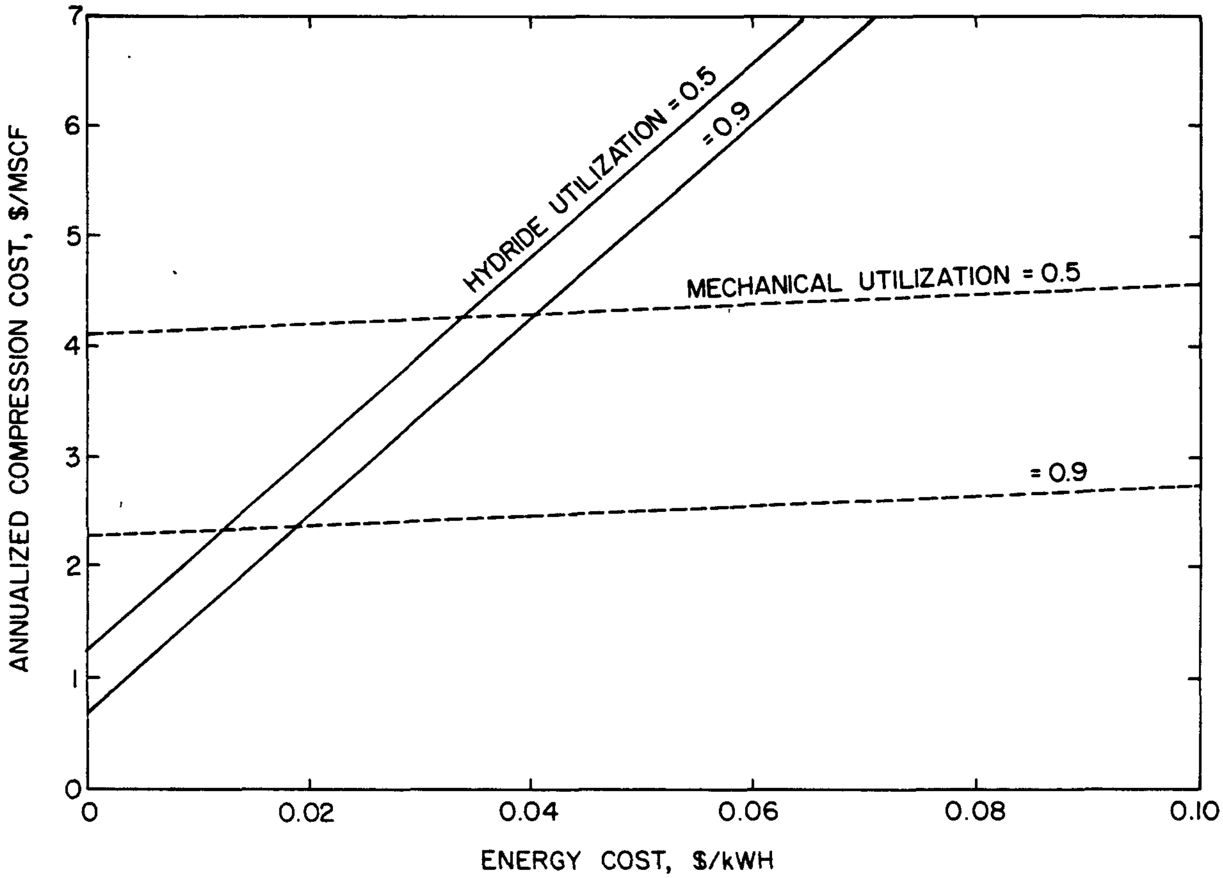

Figure 4-1. Economic Comparison of Mechanical Versus Metal Hydride Hydrogen Compressors

Section 5

DISCUSSION AND CONCLUSIONS

DISCUSSION OF TEST RESULTS

Aside from a single breakdown due to a defective heat exchanger and plug, the metal hydride compressor operated very reliably for on the order of 360 hours during testing at HTEC. No operational difficulties were encountered. Test results were consistent and repeatable (see Table C-I). Compressor hydrogen throughput at rated conditions was 2.6 SCFM, about 14% below the 3.0 SCFM specification, during the 120-hour-long test. Compressor efficiency averaged 2.1%.

The closed cycle tests were performed during the winter and early spring, while the open cycle testing was conducted during the summer. The cold water was taken directly from the tap resulting in an average cold water inlet temperature of 45°F for the closed cycle tests and 61°F for the open cycle tests. This discrepancy makes comparison of the closed and open cycle tests difficult.

INTEGRATION OF METAL HYDRIDE COMPRESSOR WITH SPE ELECTROLYZER

The approach used to interface the metal hydride compressor with the BNL SPE electrolyzer, described in Section 3, appears successful. The use of low-pressure surge tanks to stabilize hydrogen pressure despite the transient flow mismatch between the electrolyzer and compressor was satisfactory. The hydrogen purification system used also appears satisfactory.

For long-term operation it is recommended that two dryers be installed in parallel, each with isolation valves and unions. Thus, when one is depleted it can be removed from the system, replenished, and reinstalled without halting operation. In order to regenerate the dryer, purging is necessary to remove any traces of water. The purged dryer should be placed in a muffle furnace and heated to 400-600°F for at least 4 hours. Dryer lifetime is expected to be approximately 1-2 months, although larger units can be purchased. Both a color-change indicating gas dryer and an electronic hygrometer to automatically shut down the system are recommended for the compressor inlet.

A sensor to monitor the concentration of oxygen in hydrogen is recommended. In the event of a catalytic purifier malfunction, this sensor would shut the system down.

COST/BENEFITS OF METAL HYDRIDE VERSUS MECHANICAL HYDROGEN COMPRESSION

A simple economic analysis was conducted of the cost/benefits of metal hydride versus mechanical hydrogen compression. The metal hydride compressor, due to its lower capital cost and O&M expense compresses hydrogen at lower annualized cost for low energy prices. However, due to its low efficiency, the cost of compression of the hydride compressor is very sensitive to energy cost. Compression costs for the mechanical compressor, on the other hand, are quite insensitive to energy cost because of its far higher efficiency.

For example, assuming 90% utilization, the annualized cost to compress a thousand standard cubic feet of hydrogen with a metal hydride compression is $.68 when the energy is free, and $9.64 when the energy costs $.1/kWh. The annual compresion costs for a thousand standard cubic feet of hydrogen using a mechanical compressor is $2.29 when the energy is free, and $2.75 when the energy costs $.1/kWh. Using typical current prices, e.g., natural-gas-heated hot water at $0.03/KWH ($7.00/10^6 Btu and 75% burner efficiency) for the hydride compressor and electricity at $0.08/kWh for the mechanical unit, the annualized cost to compress a thousand standard cubic feet of hydrogen would be $3.37 using a metal hydride compressor and $2.48 using a mechanical compressor.

In summary, the analysis shows that a metal hydride compressor can compress hydrogen more economically than a mechanical compressor when low-cost energy is available. No general conclusion can be drawn though, because the hydride compressor compression cost is very sensitive to energy cost. Each case must be evaluated on an individual basis, e.g., via Figure 4-1.

Appendix A

THE METAL HYDRIDE COMPRESSOR EFFICIENCY

The Compressor Cycle Efficiency, E, is defined by

$$E = \frac{\text{ideal isothermal compression work}}{\text{heat input to compressor from hot water}}$$

$$E = \frac{\dot{m}_{H_2} RT \ln \frac{P_{in}}{P_{out}}}{\dot{m}_w C_{pw}(T_{in} - T_{out})}$$

where

$\dot{m}_{H_2}$, $\dot{m}_w$ = flow rates of hydrogen, water

T = hydrogen temperature

P_{in},P_{out} = inlet, outlet hydrogen pressures

R = ideal gas constant

T_{in},T_{out} = inlet, outlet hot water temperatures

C_{pw} = specific heat of water

Appendix B

TABLE OF CLOSED-CYCLE PARAMETRIC TEST RESULTS

Table B-1

CLOSED CYCLE PARAMETRIC TEST RESULTS

Date	Cycle Time (Min)	Duration (Hr)	Hot Water Inlet Temp. (°F)		Cold Water Temp. (°F)		Compressor Input Pressure (psia)	Compressor Output Pressure (psia)	Hot/Cold Water Flow Rate (GPM)	Compressor Efficiency (%)	Compressor Flow Rate (SCFM)
			In	Out	In	Out					
2/7/85	6	1	150	142	43	51	104	895	4	1.2	0.53
"	9	1.5	150	144	43	49	104	874	4	1.2	0.37
"	2	0.33	149	127	44	64	102	889	4	1.1	1.23
"	2	0.33	151	123	44	71	103	882	3	.6	0.79
2/8/85	6	1	152	140	42	52	104	898	3	1.3	0.57
"	9	1.5	151	143	43	51	104	883	3	1.2	0.37
"	2	0.33	149	122	45	71	103	904	3	.6	0.72
"	6	1	150	144	46	53	103	984	5	1.2	0.53
2/11/85	9	1.5	149	144	45	50	102	895	5	1.1	0.34
"	2	0.33	148	130	46	66	102	881	5	1.1	1.29
2/12/85	6	1	169	155	45	56	102	898	4	1.9	1.25
2/13/85	2	0.33	168	137	43	71	102	863	4	1.4	2.25
"	9	1.5	170	160	43	51	103	890	4	1.0	0.49
2/14/85	9	1.5	168	160	42	50	103	918	4	1.8	0.77
"	4	0.66	168	151	43	57	103	906	4	1.7	1.51
"	4	0.66	168	147	43	61	102	889	3	1.8	1.44
"	6	1	170	153	43	57	102	900	3	1.8	1.15
"	2	0.33	169	132	43	77	102	884	3	0.89	1.31
"	3	0.5	171	143	43	69	102	887	3	1.67	1.83
"	1	0.16	169	109	43	95	104	877	3	.03	0.06
2/15/85	9	1.5	169	158	42	52	103	899	3	1.89	0.87
"	4	.13	171	144	41	65	102	879	3	1.71	1.86
"	6	1	169	158	43	52	103	891	5	1.96	1.32
"	3	.5	167	149	43	59	101	879	5	1.88	2.19
"	2	.33	170	144	43	67	101	888	5	1.68	2.79
"	9	1.5	169	161	44	51	103	892	5	1.93	0.93
2/19/85	6	1	169	155	42	55	80	890	3.5	2.10	1.20
"	9	1.5	168	160	43	51	81	884	4	2.02	0.84
2/20/85	6	1	171	150	41	52	98	891	4.1/2.5	1.90	1.19
"	6	1	168	156	42	54	78	893	4	2.00	1.11

Table B-1 (Cont.)

Date	Cycle Time (Min)	Duration (Hr)	Hot Water Inlet Temp. (°F)		Cold Water Temp. (°F)		Compressor Input Pressure (psia)	Compressor Output Pressure (psia)	Hot/Cold Water Flow Rate (GPM)	Compressor Efficiency (%)	Compressor Flow Rate (SCFM)
			In	Out	In	Out					
2/22/85	3	.5	166	145	41	61	79	884	4	1.75	1.69
"	2	.33	170	138	42	72	78	886	4	1.40	2.03
"	6	1	170	156	42	56	121	892	4	1.85	1.28
2/22/85	3	0.5	171	148	42	63	120	887	4	1.57	1.94
"	2	0.33	167	139	43	70	120	876	4	1.22	1.93
2/25/85	9	1.5	168	160	42	50	121	883	4	1.80	0.85
2/26/85	9	1.5	169	158	44	55	98	820	4	2.53	1.45
2/27/85	6	1	170	154	44	57	98	815	4	2.52	2.03
"	3	0.5	169	144	44	67	97	795	4	2.01	2.77
"	2	0.33	168	134	45	76	97	776	4	1.40	2.53
"	9	1.5	168	157	45	55	80	815	4	2.59	1.34
2/28/85	3	0.5	166	141	43	67	79	777	4	2.16	2.62
"	6	1	169	153	44	59	79	809	4	2.58	1.92
"	2	0.33	167	134	45	76	79	783	4	1.41	2.28
"	6	1	168	153	45	59	119	802	4	2.25	1.95
"	3	0.5	167	142	45	68	118	768	4	1.78	2.55
3/1/85	9	1.5	169	158	45	56	119	802	4	2.35	1.76
"	2	0.33	168	135	46	77	118	753	4	1.30	2.56
3/4/85	2	0.33	169	136	43	74	117	778	4	1.37	2.65
"	3	0.5	170	144	45	67	101	798	4	1.86	2.5
"	6	1	186	165	45	63	101	921	4	2.99	3.02
3/5/85	9	1.5	182	168	46	59	102	915	4	3.10	2.01
"	3	0.5	176	149	47	72	101	866	4	2.12	2.73
"	3	0.5	181	152	49	75	100	882	4	2.36	3.32
"	2	0.33	182	144	48	85	101	871	4	1.69	3.28
3/6/85	4	0.66	178	154	45	69	101	891	4	2.29	2.77
"	9	1.5	183	170	47	75	102	930	2.6/3.2	3.86	1.87
"	6	1	185	160	48	71	102	908	2.8	2.7	2.39
3/7/85	2	0.33	182	134	45	88	101	885	3	.89	1.62
3/27/85	9	1.5	184	172	47	58	104	884	4.7	3.13	2.16
3/28/85	6	1	184	168	48	64	102	890	5	3.28	3.13
"	3	0.5	182	157	50	72	101	881	5	2.36	3.66
"	2	0.33	180	149	50	78	101	875	5	1.86	3.59

Table B-1 (Cont.)

Date	Cycle Time (Min)	Duration (Hr)	Hot Water Inlet Temp. (°F) In	Hot Water Inlet Temp. (°F) Out	Cold Water Temp. (°F) In	Cold Water Temp. (°F) Out	Compressor Input Pressure (psia)	Compressor Output Pressure (psia)	Hot/Cold Water Flow Rate (GPM)	Compressor Efficiency (%)	Compressor Flow Rate (SCFM)
4/2/85	6	1	169	156	49	61	103	891	3.8	1.52	0.95
"	2	0.33	167	138	48	76	102	872	3.8	1.18	1.64
"	4	0.66	170	150	50	68	103	877	4	1.55	1.65
4/3/85	9	1.5	168	160	50	66	104	977	3.8	1.37	0.55
"	6	1	171	161	50	67	103	977	4	1.5	0.77
"	3	0.5	170	148	50	82	102	988	4	1.25	1.52
"	3	0.5	168	148	51	68	102	981	4	1.27	1.2
4/3/85	6	1	169	156	51	62	82	989	3.6/4	1.40	0.73
4/8/85	9	1.5	169	161	51	57	79	986	4	1.40	0.47
"	3	0.5	170	151	51	69	77	991	4	1.57	1.33
"	2	0.33	174	144	51	78	77	992	4	1.24	1.61
4/9/85	9	1.5	171	163	51	59	120	980	4	1.26	0.51
"	6	1	170	160	53	62	120	975	4	1.36	0.77
4/10/85	3	0.5	172	152	51	69	119	985	4	1.31	1.38
"	2	0.33	169	142	51	75	119	980	4	1.06	1.46
4/11/85	9	1.5	171	161	52	59	101	984	3.6/4.1	1.24	0.50
"	6	1	168	157	52	62	101	983	3.8/4.1	1.36	0.72

Appendix C

TABLE OF OPEN-CYCLE PARAMETRIC TEST RESULTS

Table C-1

OPEN CYCLE PARAMETRIC TEST RESULTS

Date	Cycle Time (Min)	Duration (Hr)	Hot Water Inlet Temp. (°F) In	Hot Water Inlet Temp. (°F) Out	Cold Water Temp. (°F) In	Cold Water Temp. (°F) Out	Compressor Input Pressure (psia)	Compressor Output Pressure (psia)	Hot/Cold Water Flow Rate (GPM)	Compressor Efficiency (%)	Compressor Flow Rate (SCFM)	Electrolyzer Flow Rate (SCFM)	Dewpoint °F
8/16/85	3	1.5	183	165	61	77	104	1030	5	1.75	1.5	1.7	-48
"	3	2	188	166	59	79	104	1009	5	2.2	2.2	1.6	-49
8/18/85	3	4	188	162	75	83	104	1016	4	1.8	1.8	1.8	-46
8/19/85	3	4	188	158	61	88	108	1010	3	1.6	1.5	1.8	-47
8/20/85	5	4	187	170	61	77	107	1014	4	2.3	1.5	1.8	-46
8/21/85	5	4	187	165	60	78	103	1008	3	2.0	1.2	1.6	-47
8/22/85	3	1.5	168	147	63	82	101	1010	3	1.2	0.8	1.0	-46
"	3	4	187	157	60	87	104	1008	3	1.6	1.4	1.4	-47
8/23/85	5	4	187	166	60	79	104	1009	3	2.0	1.2	1.5	-47
8/25/85	5	1.5	168	154	63	76	106	1007	3	1.4	0.5	0.9	-46
"	5	4	187	170	58	74	105	1006	4	2.2	1.4	1.5	-48
8/26/85	3	1.5	168	151	62	77	101	1008	4	1.4	0.9	1.2	-47
"	3	4	188	162	59	82	100	1008	4	1.8	1.7	1.8	-46
8/27/85	2	1	168	152	63	78	105	1008	4	1.3	0.8	1.0	-47
"	2	1.5	168	157	59	69	101	1007	4	1.4	0.6	0.6	-47
8/28/85	3	1.25	177	158	62	78	101	1008	4	1.6	1.2	1.5	-46
"	3	1.5	185	154	58	87	101	806	4	2.4	3.1	1.9	-48
"	3	1	187	159	58	83	102	911	4	2.2	2.4	1.9	-48
8/29/85	4	1.5	187	168	61	79	102	1010	4	2.1	1.6	1.4	-47
"	3	1.5	188	163	58	81	102	1008	4	1.8	1.7	1.8	-48