N63 22142

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Code 1

NASA CR 50544

OTS PRICE

XEROX $ 3.60 ph

MICROFILM $ 1.10

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DIVISION OF UNITED AIRCRAFT CORPORATION

EAST HARTFORD 8, CONNECTICUT, U. S. A.

Final Report
on Design and Development of
Hydrogen-Oxygen Fuel Cell Powerplant
Report No. PWA-2081

NASA Contract No. NAS3-1724

June 15, 1962

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EAST HARTFORD • CONNECTICUT

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FOREWORD

This final technical report was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation, East Hartford, Connecticut, in compliance with Contract NAS3-1724. It covers the technical accomplishment on the development of a hydrogen-oxygen fuel cell powerplant throughout the entire contract period from July 1, 1961 through May 15, 1962.

ABSTRACT

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Initial design efforts for the 250-watt experimental powerplant included the 15-cell module and oven, hydrogen circulation pump, powerplant controls and electrical equipment, and system heat exchangers. During the design phase of the contract period, development data and testing experience were gathered on breadboard components.

Successful manufacture of the designed components for the 250-watt powerplant, followed by bench testing of the individual units, led to early demonstration of rated power output on a complete powerplant. The only major item changed from the original design was the hydrogen circulation pump. A sliding vane design was substituted for the original centrifugal type in order to lower parasite power consumption.

Automatic operation of a powerplant was achieved with all parasite loads supplied by the fuel cell. This success led to the substitution of operation of two powerplants in parallel (electrically) for 50 hours for the Task 2 powerplant design originally scheduled. This program was successfully completed during the final contract quarter. In further testing as requested verbally by NASA personnel while visiting Pratt & Whitney Aircraft Division to witness a powerplant in operation per Article IX of the subject contract, one of the fuel cell modules was deliberately short-circuited.

Task 1 Test Program

	Fuel Cell	Components	Powerplant
Goal - hours	3500	1000	500
Total contract - hours	4331	2436	691

Task 2 Test Program

	Parallel Powerplant Operation
Goal - hours	50
Total hours	62 (deliberate short circuit ended program)

Future programs which might be conducted as an extension of the work on a 250-watt hydrogen-oxygen fuel cell powerplant are outlined in Section VI of this report.

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I. INTRODUCTION

Objective

The objective of this program was to design, fabricate and construct a hydrogen-oxygen type fuel cell powerplant for testing purposes which would establish the feasibility of the fuel cell power supply for manned space vehicle applications. Upon completion of the development phase, an endurance run was conducted on two powerplants electrically powering a common load.

Scope of Program

The program to meet the above stated objectives consisted of the following specific tasks:

Task 1 - Design, fabrication, and testing of a low pressure hydrogen-oxygen, experimental fuel cell powerplant with the objective of providing 250 watts at 12 ±1 volts, and demonstrating a minimum operating efficiency of 50 per cent at maximum load conditions.

The test program included:

a) 4331 hours of single and multicell testing.
b) 2436 hours of testing on controls, pumps and heat exchangers.
c) 691 hours of testing of experimental powerplants.

Task 2 - The original requirement of Task 2, to prepare a preliminary design of a prototype hydrogen-oxygen fuel cell, was cancelled in favor of 50 hours of parallel powerplant testing.

This test program included:

a) 62 hours of parallel powerplant operation.
b) Deliberate short circuiting of one of the two parallel powerplants.

II. DESCRIPTION OF FUEL CELL POWERPLANT

The 250-watt fuel cell powerplant designed, constructed, and tested under the terms of this contract consisted of a module assembly for power production, a circulation loop for heat rejection and water removal, and controls for reactant pressure and flow regulation.

A schematic drawing of the powerplant is presented in Figure 1. Figure 2 is a photograph of a 250-watt experimental powerplant installed in a fuel cell test stand.

The fuel cell module portion of the 250-watt powerplant consisted of 15 pairs of electrodes connected electrically in series to provide the desired voltage and power. Each pair of electrodes consisted of a hydrogen electrode with gas supply and exhaust ports, an oxygen electrode with similar gas ports and an electrolyte compartment with an electrical insulating material between electrodes. Oxygen supplied to a cell reacts with water in the KOH electrolyte at reaction sites in porous nickel oxide electrodes, and hydroxyl ions are created. The reaction requires electrons which are provided through the external load from the hydrogen electrode. After formation the hydroxyl ions migrate through the electrolyte to the reaction sites in the porous nickel hydrogen electrode, where they combine in a second reaction to form water and provide electrons to the external circuit. The overall reaction combines hydrogen and oxygen to form water, electricity and excess heat. The module assembly includes any pressure vessel and insulation required for the desired operating conditions. For the experimental powerplant the operating conditions selected were: 500°F cell temperature, atmospheric electrolyte pressure (approximately 20 psia reactant gas pressure), and 85 per cent electrolyte concentration.

The hydrogen circulation loop provides a means of rejecting excess heat and removing the exhaust product, i.e., water. The loop consists of a hydrogen circulation pump, drive motor, heat exchangers and a water separator. The hydrogen pump circulates a hydrogen-water vapor mixture through the gas space of each hydrogen electrode at a rate several times the hydrogen consumption rate. The low concentration of water vapor in the incoming gas mixture permits the diffusion of water vapor from the porous electrode structure, and the enriched mixture of water vapor and hydrogen is purged from the cell to the heat exchangers. The first exchanger, a regenerator, is included to conserve heat at low power conditions by transferring heat from the outgoing hydrogen-water vapor mixture to the incoming mixture. The second heat exchanger rejects excess heat to an external sink and condenses the water vapor, thus separating the hydrogen-water mixture. The recirculated hydrogen, now containing a low water vapor concentration, is pumped back to the fuel cell either through the regenerator or not, as the operating conditions may require. The reactant controls consist of differential pressure regulators which maintain a constant discharge pressure with respect to a reference pressure regardless of the quantity of flow. The powerplant controls consist of a hydrogen flow control valve to regulate the quantity of recirculated hydrogen, a radiator bypass valve to adjust the water content in the recirculated mixture, a regenerator selector valve to provide for conservation of heat at low power conditions, and standby heater controls to maintain operating temperatures under no load conditions.

The original module design incorporated Fiberglas-coated nichrome wire heaters for heating purposes. These were later changed to Teflon-coated wire heaters which were expected to be better able to withstand the corrosive effects of potassium hydroxide.

Early electrode designs incorporating brazed dimples did not provide the necessary structural integrity desired. Techniques were evolved which allowed successful electron beam welding of the hydrogen electrode and resistance brazing of the oxygen electrode sinters to their respective backup plates.

During the final testing phases of the powerplant, the individual cell spacer rings were redesigned so that the load would be applied to the round portion of the Teflon o-ring, instead of to the flat portions on either side, as originally designed.

A hydrogen circulation system was designed utilizing a high speed centrifugal pump for gas pumping and water separation, a condenser and condenser bypass valve for water condensation and gas temperature control, a paracymene-operated flow valve for controlling the amount of recirculated hydrogen, and a paracymene-operated regenerator bypass valve for directing the flow around or through the module regenerator. The centrifugal pump was replaced with a sliding vane type pump to reduce the parasite power loss. The water separator was developed on a separate basis and, since this powerplant always had the benefit of gravity, was never tested on a powerplant circulation loop.

Paracymene-operated heater switches were replaced late in the program with mercury column type Vap-Air heater control switches. The latter units, although not used extensively in this program, performed their desired function.

With the information gathered during the testing portion of the program, it is felt that the following designs are worthy of further investigation.

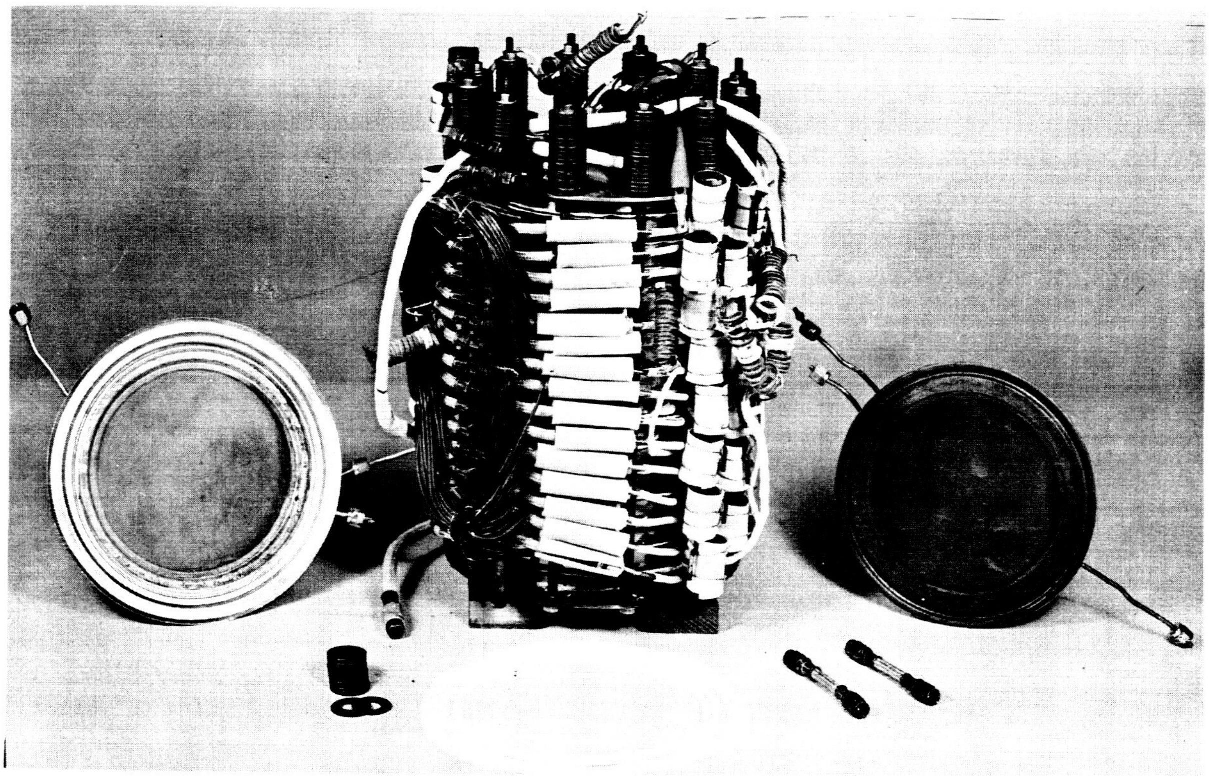
1) An electrode with a completely sealed electrolyte compartment,
2) A pressurized module and system design with the regenerative bypass valve mounted internally (possibly eliminating the flow control valve),
3) A double inlet/discharge sliding vane pump with a sealed electric motor, and
4) Bimetallic control system components utilizing direct temperature signals as a basis for scheduling flows.

IV. FABRICATION

A review of each section of the powerplant will be presented, not with the idea of discussing again the actual method of construction which was discussed previously in the second quarterly report submitted under Contract NAS3-1724 (PWA 2027), but to note the progress made during the program towards improving these components and to comment on components that were changed.

A. Fuel Cell Module

1. Anode (hydrogen electrode)



250-Watt Fuel Cell Module and Electrodes

Originally designed state-of-the-art Pratt & Whitney Aircraft Division-manufactured hydrogen electrodes were fabricated by brazing the dimpled sinter retaining dish to the gas backup plate. An alternate design using vendor-supplied dual porosity disks was investigated. This program led to the development of the electron beam welding techniques for attaching the sinter to the gas backup plate. Emphasis during the latter phases of the program was directed toward the beam-welded electrode since its overall cost was less than that of previous designs.

2. Module Spacer Rings

The module spacer rings were redesigned when a review of the tolerance buildup between the electrode assemblies, Teflon o-rings and the spacers themselves, determined that sealing load was being applied to the flat portion of the seal. The desired seal loading area was the o-ring portion, since it was there that the required load to seal was the smallest, and the allowable compression before shorting, the greatest.

3. Electrolyte Seal

A great deal of development effort was concentrated on the electrolyte seal in an attempt to provide positive sealing with the least complicated method of assembly and parts manufacture. A design incorporating a wave washer for load followup on a tapered, wedge-shaped, Teflon seal, was found to be a positive sealing device, but was awkward from an assembly standpoint. Thus, the original electrode gas backup plates were designed to accept several different shapes and combinations of Teflon seals. These included:

1) Flat single gaskets,
2) Flat stacked (overlapped) seals,
3) Round solid o-rings,
4) Round hollow o-rings, and
5) O-rings with flat gaskets.

Early testing indicated that a combination of the flat gasket for electrical insulation and the round solid o-ring for sealing was the most desirable. The combination of a round o-ring with flat ears was available for testing during the third quarter. A dimensional tolerance buildup leading to electrical short-circuiting caused early difficulties. The part was redesigned coincident with the module electrode spacer rings and tested successfully in the fourth quarter.

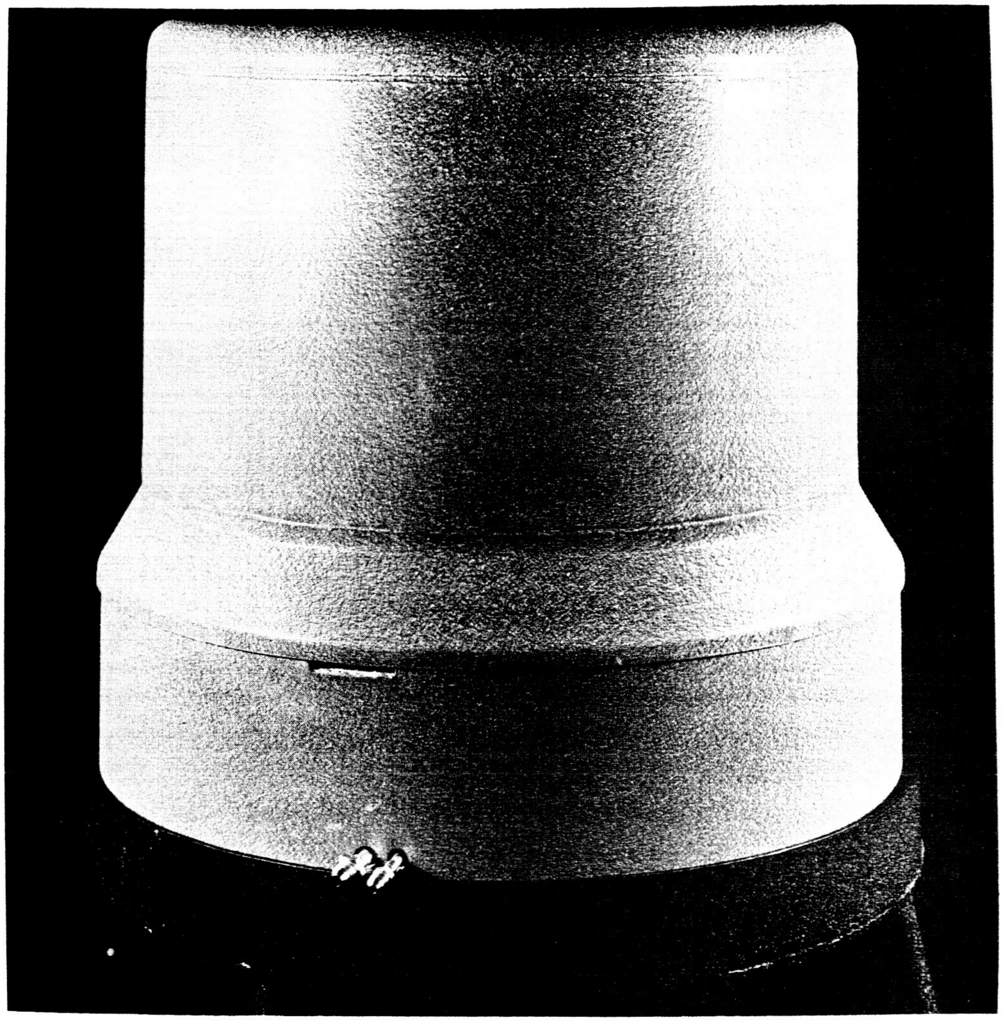
4. Electrode-Manifold Connectors

The original manifold-to-electrode gas supply tubes were vendor-furnished Teflon hoses. Although these hoses performed satisfactorily, it was felt that a more sophisticated connector/ insulator was needed for practical applications. Aluminum oxide electrical insulators were assembled by brazing into a gas supply manifold and successfully tested on powerplants. This manifold proved to be leak free, durable, and required less space than its predecessors.

5. Heating Elements

Individual mats of Fiberglas-coated nichrome wire were designed and utilized for internal heating purposes on all powerplants. Suspected short circuits and localized arcing was traced to these heaters which had been damaged by spillage of potassium hydroxide. Revised heating elements consisting of Teflon-coated wires were then purchased. Local arcing and short-circuiting within the module disappeared.

B. Fuel Cell Module Insulating Jacket Assembly

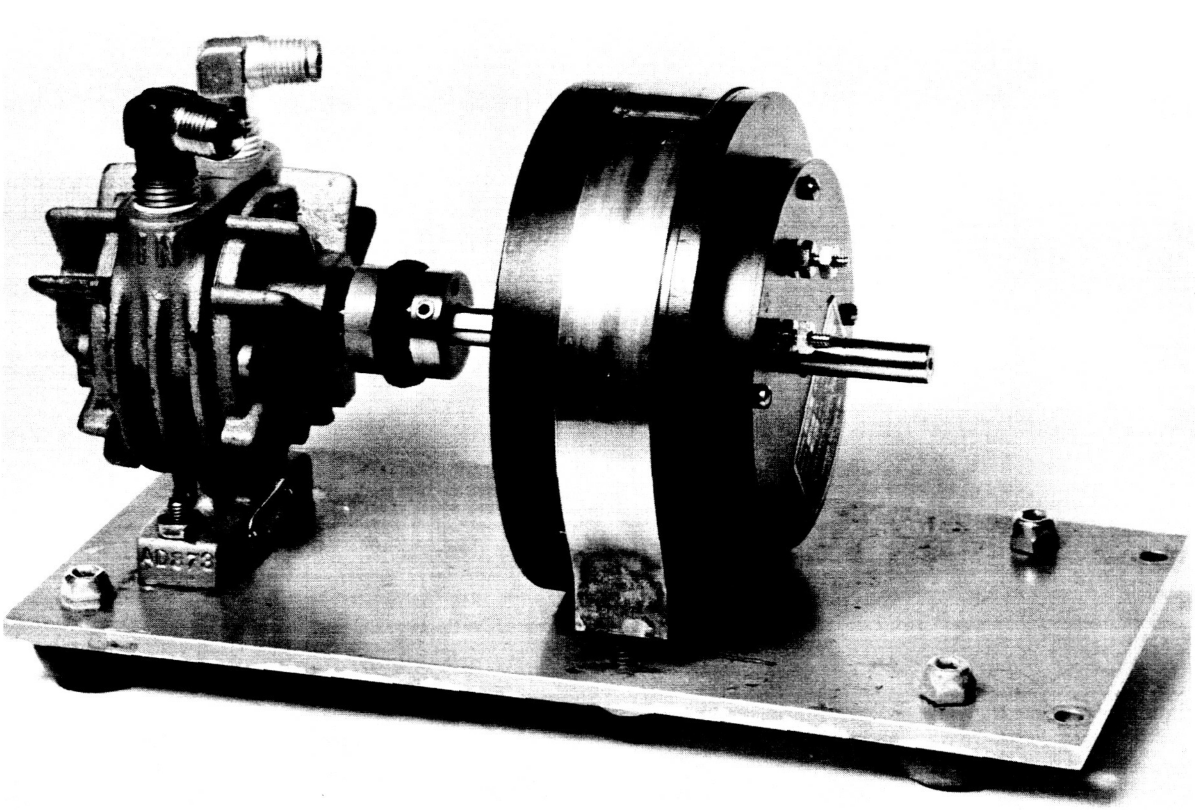


Module Insulating Jacket with Regenerator

1. Cover and Base

With the exception of one block of Min-K insulation in the base assembly, the insulation used in the tested assemblies was Thermobestos. Since the heat lost through this insulation proved to be greater than calculated, the base and cover were redesigned to accept Min-K type insulation throughout.

C. Hydrogen Circulation Pump



Sliding Vane Pump

Development efforts to reduce the wattage requirements of the originally selected high speed centrifugal pump appeared to be too lengthy to produce the desired results for this size powerplant in the contract period. A commercially available, non-sealed, sliding vane pump was purchased and mounted in a container along with a 12-18 volt DC motor. The pump and motor were run submerged in a hydrogen atmosphere created by leakage past the shaft ends of the unsealed pump bearings. Power requirements were acceptable and additional units were purchased and used successfully throughout the remaining contract period.

V. TEST RESULTS

Prior to the availability of hardware designed specifically for the 250-watt powerplant, tests were conducted on breadboard components (available hardware of an earlier design). These tests included single cell, multicell, and multicell modules with a hydrogen circulation loop and reactant pressure regulators. As experimental powerplant parts became available, a similar program of single cell, multicell, component and circulation loop tests was run. The primary test objective, a 250-watt power plant test was reached during the third quarter. Automatic operation was accomplished with all parasite loads powered by the fuel cell, and the design power output goal was reached.

A. Experimental Powerplant Components

1. Breadboard Powerplant

The breadboard powerplant fuel cell electrodes (described completely in report PWA-2008, the first report prepared under the terms of this contract) were mounted vertically in a nickel tank containing molten 85 per cent potassium hydroxide at 500°F. This type of electrode assembly was used in single and multicell tests to gather data for the design of the proposed experimental powerplants. Single cells were utilized to determine the effects of temperature on maximum cell wattage and on individual electrode life. One cell operating at 425°F demonstrated 1500 hours of endurance before the test was transferred to the Pratt & Whitney Aircraft Division. program and run an additional 700 hours.

Breadboard testing was terminated for two reasons:

1) A 14-cell unit demonstrated a 250-watt output during a 145-hour run.
2) Experimental powerplant hardware was available in sufficient quantities to begin component testing.

2. Experimental Powerplant

a. Fuel Cell Module

Early development of the 250-watt experimental fuel cell powerplant was conducted along lines similar to those followed during the breadboard powerplant initial phases, but at a more rapid rate. Testing progressed from single cells through 6-cell assembly tests to the final 15-cell version.

1) Single Cell Tests - Single cell testing fell into the three basic categories of sealing, filling and performance. A total of 1046 hours of single cell testing was done in support of the powerplant effort.

2) Electrolyte Seals - The originally proposed hollow Teflon o-ring with thin ears for insulation properties proved impractical to mold, and impossible to machine. As previously detailed in this report, as well as in the 2nd and 3rd quarterly contract reports, various combinations of flat gaskets and o-rings were successfully tested. The preferred design, from both assembly and sealing standpoints, which was developed during this program, was the solid o-ring with thin ears. Although much effort was expended trying to mold this particular configuration, no satisfactory part was made. Consequently, all of this type of o-ring tested were machined from a tubular section of extruded Teflon.

3) Filling Procedures - A considerable amount of effort was devoted to determining a consistent method of filling the electrolyte cavity formed between the two electrodes. Although several alternate approaches met with fairly good success, the most reliable procedure was the most complex. This procedure involved: a) tilting the cell 5 to 10 degrees, b) inserting a previously cast KOH wafer between the cells, c) heating the cell with external heaters (better results obtained with external heaters as compared to the mesh type used between the cells in a module) until the KOH wafer has melted, and d) pour 85 per cent KOH into the fill cap.

   Difficulties were encountered during filling complete module assemblies with only internal heaters, since the KOH would solidify in the fill and/or vent cup tube lines and trap air pockets inside of the cells. This problem was eliminated by supplying external heater power during the filling operation.

4) Multicell Tests - 6-cell assemblies were built prior to attempting 15-cell module stackups, in an effort to determine possible problem areas. Early success led to the building of the first 15-cell module assembly early in the 3rd quarter. The first 15-cell module met the predicted performance estimates as shown in Figures 3 and 4.

5) Module Insulating Jacket - As previously mentioned in this report, the heat loss through the Thermobestos walls of the oven cover and base of 315 BTU/hour exceeded the calculated 250 BTU/hour. Further increases in heat loss were encountered when the great amount of module instrumentation made necessary for program development was routed out of the inner recesses of the oven through the split between the top cover and the oven base. Although successful self-sustaining operation was attained, it is felt that the self-sustaining range could be extended with better insulation.

6) Hydrogen Circulation Pump- Development of the high speed centrifugal pump and separator was carried sufficiently far to determine that the pump would provide for the designed head initially considered necessary for the powerplant (10 inches of water) as well as satisfy the flow requirements. Power consumption however was well in excess of the 25-50 watt level desired for this powerplant.

An alternate configuration consisting of a commercially available sliding vane air compressor coupled directly to a printed circuit armature DC motor was assembled and tested. Power consumption was less than 25 watts over the flow and pressure range needed to satisfy all running regimes of the 250-watt powerplant. Since the motor and pump shaft ends were not sealed, some concern was felt early in the program over the life expectancy of the motor brushes. Both the motor and pump were running in a sealed container pressurized to system pressure levels by gas leakage around the ends of the pump shaft. No motor failures were encountered that could be attributed to brush wear. This motor/pump combination was used during complete powerplant runs made in fulfillment of the contract requirements.

3. Controls

During the contract period, work on the control components centered on three main areas:

1) Establishment of the control component requirements,
2) Design, fabrication, and development testing of possible control systems, and
3) Demonstration of automatic control system operation on a 250-watt powerplant.

Since the major emphasis of this contract concerned a fuel cell feasibility study, a full scale development program on control components was not possible. The amount of development work actually accomplished was sufficient to provide satisfactory preliminary results in the three work areas listed above.

The feasibility of the control mode selected has been demonstrated by the more than 750 hours of control component operation during actual powerplant module testing. During three hundred of these hours the components were operating automatically.

The final control system selected for automatic control of the 250-watt powerplant consisted of the following components:

1) Hydrogen reactant gas pressure regulator,
2) Oxygen reactant gas pressure regulator,
3) Regenerator bypass control,
4) Recirculation flow control,
5) Condenser bypass valve, and
6) Mercury thermostats and electrical relays for heater control.

Additional bench and powerplant testing with more extensive use of instrumentation is necessary to document completely the control component scheduling necessary for most efficient operation.

No detailed description of the control system concept has been provided in the first three quarterly reports. Since this system has now proven its feasibility, a detailed description of the parameters considered and results obtained is presented in the final report. During the early part of the program considerable work was done to define the control system and component requirements based on analytical studies. The studies showed that the module reactant gas pressure would have to be regulated to 7.5 ±0.5 psig over a flow range from zero to twice design flow, with a regulator supply pressure range of 30 to 100 psig.

The regenerator bypass valve, whose main function is to control the module temperature, was designed to vary the recirculated hydrogen flow entering the module either around the regenerator (at high module temperatures) or through the regenerator (at reduced module temperatures). Its operating temperature range was 495 to 500°F.

A means of controlling the fuel cell electrolyte concentration was also indicated in the study. The control of concentration was accomplished by using a recirculation bypass control similar in design and operation to the regenerator bypass valve. By bypassing part of the pump discharge flow back to the pump inlet, and thereby controlling the amount of hydrogen gas flow in the recirculating loop, control of electrolyte concentration is effected. The valve provides a minimum recirculated loop flow at 500°F and a maximum flow at 480°F module temperature.

The study also indicated the need for a control to maintain the recirculating pump inlet temperature at a fixed value in order to establish the desired relationship between recirculation loop flow and rate of water removal from the electrolyte. This function was accomplished by mixing hot gas from the condenser inlet line with the cool flow of gas leaving the condenser.

The final requirement established by the study concerned the module internal heaters. Study results showed that the heater controls should be used to maintain a module temperature of 480 to 500°F. The heater controls were designed to operate in that range.

Powerplant testing during the contract period provided preliminary verification of the analytical requirements for the reactant pressure regulators and module internal heater ranges. The test results indicated that the regenerator control would produce satisfactory results over a temperature operating range of 490 to 495°F. The recirculation control temperature operated effectively between 485 and 490°F and its operational setting was changed to reflect this development.

Two major problems were encountered in the design, fabrication and testing of the control components, and satisfactory solutions to both problems were found.

The first problem involved the need to establish background knowledge on the design of valves having zero leakage, low velocity and low flow capacity. In addition, testing techniques for these conditions had to be developed. Design knowledge was obtained by running various valve designs in test rigs and supporting the tests with predicted analytical results. The testing technique thus developed on an empirical basis led to successful control development.

a. Hydrogen and Oxygen Supply Pressure Regulator

The original hydrogen and oxygen reactant gas regulator (same unit for both gases) designed for use on the 250-watt powerplant exhibited excessive supply and vent valve leakage. In addition to the excessive valve leakage, excessive hysteresis was experienced during valve regulation. Because of these problems a decision was made to concentrate the development effort on a regulator of earlier design that had demonstrated lower leakage rates. During the contract period, continued development of the selected regulator showed the need for revisions in the basic design which would lead to a zero leakage unit with the desired regulation characteristics. These revisions consisted of 1) replacing the cone seat valve with a flat-faced valve having a rubber seat, 2) changing from a Teflon to a neoprene rubber diaphragm, 3) incorporating finer surface finishes on all sliding surfaces, and 4) reducing the diaphragm loading spring rate. Satisfactory results have been obtained on the regulator during more than 1400 hours of bench and powerplant running. In addition to the normal bench and powerplant operation a total of 103,850 cycles have been obtained over a flow range from zero to double the design flow with no failures of the regulator. A typical regulation curve is shown in Figure 5.

b. Regenerator and Recirculation Flow Bypass Valves

Both controls are basically the same design. The major difference is the use of internal lever stops on the recirculation control and no stops (ability to produce zero flow in either flow path) in the regenerator control.

The original design used metal spherical half-ball valves seating on metal cone-shaped seats. Excessive friction and high leakage were experienced. A change to a flat-faced rubber-coated valve and a flat thin-lipped seat eliminated the leakage problem. A change to stainless steel material and better surface finishes on all moving parts reduced the friction to acceptable levels. Nonrepeatability and apparent setting shifts were experienced with the temperature-sensing paracymene system. A change of bulb location on the module to the center of the electrode stack greatly improved the correlation between bench and powerplant settings. Part of the inconsistencies experienced with the paracymene system were traced to the filling procedures. A change from gravity filling of an evacuated system to pressure filling and the addition in the paracymene line of a compensating bellows (basically an added adjustable volume) eliminated virtually all of the problems. A typical performance curve for both the regenerator bypass and recirculation flow control is shown in Figure 6.

c. Condenser Bypass Valve

Little trouble was experienced on this control during the contract period due to the amount of powerplant running time accomplished at recirculation pump inlet temperatures of 80°F or higher. Above 80°F inlet temperature the unit stops the hot gas bypass flow around the condenser and passes flow directly from the condenser exit to the pump inlet. Approximately 240 hours of satisfactory operation were obtained during the final quarter of the contract period. A typical performance curve for the condenser bypass control is shown in Figure 7.

d. Thermostatic Heater Switches

In order to simplify the paracymene system and use an existing design of proven reliability and simplicity, a change from the original heater switch design was made. The paracymene bellows and microswitch were changed in favor of a mercury type thermostat coupled to an electrical relay.

These units have successfully scheduled the heater operation during powerplant running to maintain the module temperature at the proper level.

B. Experimental Powerplant

The first complete powerplant initially tested under load conditions on January 15, 1962, contained a pretested 15-cell module assembly. Although running was accomplished without automatic controls, a maximum gross power output of 300 watts was demonstrated at 12.6 volts, as shown in Figures 3 and 4. A net power output of 250 watts was attained corresponding to 280 watts gross power. The 30 watts difference represents the power consumed by the pump. Previous powerplant running was described more completely in report PWA-2063, the third report published during the contract period.

Later powerplant programs were expanded to include more complete and sophisticated instrumentation to provide data on:

1) amount of hydrogen flow through the pump,
2) amount of hydrogen flow through the flow control to the condenser inlet line,
3) amount of hydrogen flow through the flow control to the regenerator control,
4) amount of hydrogen flow through the regenerator and the regenerator heat transfer characteristics,
5) pressure losses through the various portions of the control system,
6) operational range of the control units,
7) heater requirements and heater control responses, and
8) water removal and thermodynamic characteristics of the hydrogen circulation loop.

These varied programs led to the running of a completely automatic powerplant which contained the following control system:

1) paracymene-actuated flow control,
2) paracymene-actuated regenerator control
3) oxygen pressure regulator,
4) hydrogen pressure regulator,
5) condenser bypass valve,
6) "Vap-Air" mercury column heater switches, and
7) DC motor-powered hydrogen supply pump, driven by module power.

With the module gross power set at 278 watts, a completely automatic run was made. During this run, the heater controls turned the heaters on and off at 480 and 490 respectively. The flow control operational range was 488 to 492 during which it shifted the major portion of the flow from the bypass loop (flow control to condenser inlet) to the regenerator control valve. The regenerator control valve, operating over the 500 to 494 range, then directed the gas either around, or through, the regenerator. At this maximum load condition, an overall system thermal efficiency of 54.2 per cent was attained. The data for this run is graphically presented in Figures 8 and 9.

C. Experimental Powerplant Parallel Operation

As a last test in the program, two powerplants were operated electrically in parallel to demonstrate both the ability to share a joint load as well as the response characteristics of the dual system during intentional short-circuiting of one powerplant. A total time of 62.5 hours of parallel operation was accumulated on two 250-watt output modules both supplying power to a common load. The average net power supplied during this period was 269 watts with a 47 and 53 per cent power distribution between the two powerplants.

After completing the 62.5 hours of parallel operation, two intentional short circuits of 5 and 11-minute durations were imposed on the same module. Individual powerplant protection against reverse current during short circuit was provided by two 15-ampere diodes connected in parallel in each circuit. Diodes were selected for this purpose instead of a reverse current relay since instantaneous isolation was desired. Relays require a small percentage of reverse current in order to activate the solenoid-operated latch. The disadvantage of diodes, however, is the higher power loss associated with their characteristic voltage drop.

Prior to the short circuit test, a total of 269 watts were furnished jointly by the two parallel-connected modules. In addition to the load power, an additional 20.2 and 24.0 watts were dissipated in the diode components and adjustable pump rheostats respectively. When the short circuit was imposed, the unaffected module responded within the 0.03 second response time of the recording unit to provide 242 watts net power to the load. The small load power discrepancy between the shorted and nonshorted condition was attributed to the increase in diode loss from 10.6 to 20 watts associated with the increased current capacity of the single supply module. Following the removal of the short, the mutual load was established at 245 watts.

Transient records were obtained during the shorting procedure but partial malfunction of the instrument limited the scope of information obtained. The response characteristic record of the shorted module was valid and the replotted results are indicated in Figures 10 and 11 for the first short circuit test.

D. Electrode Failure Analysis

In the time interval allowed for completion of this contract, considerable advances have been made in the art of manufacturing durable, high performance electrodes. Although several problem areas were investigated, a definite trouble area was found and corrected during the final weeks of the program.

Up to this point, inexplainable short circuiting of cell assemblies while in module builds had led to several module disassemblies. Unfortunately, the shorted cells normally performed satisfactorily as single cells. Disassembly of the single cells normally proved inconclusive, also. A design review of the cell spacer drawing indicated load was being applied to the flat portion of the seal, and at the corners of the o-ring groove. This type of loading caused the outside edge of both plates to be pinched together, cutting the electrically insulating Teflon and short circuiting the cell. All module spacers and end covers were reoperated to relieve this condition and no further short circuiting due to cut gaskets was evidenced.

With the elimination of the mechanical short circuiting problem, there arose a chance to clearly observe, for the first time in this development program, the consequences of nickel and oxides of nickel in the electrolyte solution. While this problem had been noted on earlier types of "open pot" fuel cells during development testing, it was believed to be a function of not only temperature, but also of the nickel surface in contact with the electrolyte, the nickel surface being the walls of the electrolyte tank. In this program, however, and concurrently with the mechanical short circuits, the performance of various pairs of electrodes of the type used in the powerplant program was noted to fall slowly with time during cell operation at 500°F. While disassembly indicated that the electrolyte contained nickel particles, the cells also showed evidence of mechanical short circuiting. The effect of lowering the temperature was investigated and reported in the second quarterly report for this contract and it was shown that deposition was not a problem at 425°F. No further efforts were expended on the problem with monies from this contract. It was felt that basic electrochemical research was not a proper charge against this contract.

Difficulties of a magnitude great enough to require electrical removal of two cells from a module, occurred during the parallel powerplant run at 500°F. Post test inspection revealed sufficient quantities of nickel particles in the electrolyte to have caused the gradual deterioration in cell performance. These two cells are the only cells in the entire program where no other cause for failure could be determined.

A description of typical electrode failures investigated during the program with corrective action taken is listed below:

Oxygen Electrode

Type I - Failure of brazed dimples between the electrode support plate and the sinter backup plate. The braze process was changed from an oven braze to a resistance braze and from point to line contact.

Type II - Failure of the sintered bond between sinter material and electrode support plate. This type of failure has been traced to improper and incomplete flame-spraying of the sinter disk backup plate.

Hydrogen Electrode

Type I - Same failure as noted for Type I oxygen electrodes, This problem was solved when an alternate hydrogen sinter was developed and used extensively throughout the remainder of the program.

Type II - Failure of electron beam weld between the support plate and the sintered element. Increased density material properly oriented in the sintered structure to allow positive adherence of the two pieces has cured this problem.

Poorly performing cells caused by gas pockets in the electrolyte can be avoided by proper inspection, filling and heating techniques. Internal short circuiting caused by deflecting sinters was eliminated by improving the brazing and beam welding techniques.

Future programs utilizing the manufacturing techniques developed in this program should minimize failures caused by structural defects. Improved inspection techniques, more properly oriented by this program experience, should eliminate the remaining electrodes of questionable quality.

E. Test Time

The table below summarizes the time accumulated during the last contract period.

1. Experimental Powerplant			241.9
Modules		241.9	
Hydrogen Circulation Loop		260.1	
Controls		1,550.0	
Pressure Regulators	484.0		
Flow & Regenerator Bypass Controls	484.0		
Heater Controls	340.0		
Condenser Bypass	242.0		
2. Experimental Powerplant Components			602.3
Fuel Cells		143.3	
Single Cells	141.7		
Multicells	1.8		
Hydrogen Circulation Loop		0.0	
Pump		0.0	
Controls		459.0	
Pressure Regulators	149.0		
Flow & Regenerator Bypass Controls	285.0		
Heater Controls	5.0		
Condenser Bypass	20.0		
3. Breadboard Powerplant			0.0
4. Breadboard Powerplant Components			0.0
Total Hours			844.2

Total test time on the contract to date:

First Quarter	1,456.5
Second Quarter	3,643.6
Third Quarter	1,514.0
Fourth Quarter	844.2

VI. FUTURE PROGRAMS

Several unexplored regions of fuel cell powerplant operation remain to be investigated. Possible programs utilizing the present 250 watt-powerplant hardware might include:

1) Definition of the self-sustaining region with an oven containing Min-K insulation,
2) Definition of the self-sustaining region at lower temperatures such as, 475°F, 450°F, 425°F and 400°F,
3) Revisions to the control system, i.e., reduce number of components necessary and mount controls internally for better heat conservation,
4) Investigate a wide range of condenser exit temperatures, with and without a simplified control system, to determine the actual variation in electrolyte concentration,
5) Calibrate over a wide range of power levels with a constant speed hydrogen circulation pump to determine the electrolyte concentration variation, and
6) Operation of two or more modules in parallel to fully document expected problem areas.

Continued development of the 250-watt powerplant size module electrodes into a sealed, diaphragm-type electrode would quickly lead to zero gravity testing of a module in an orbiting space vehicle. Additional effort would be required for a complete system suitable for space type operation.

With the manufacturing and systems experience gained during development of the 250-watt powerplant, future development programs should be aimed at improving and simplifying the present system, or at initiating development of the "next generation" of fuel cell, both for space and earth bound applications.

In order to operate a completely automatic fuel cell powerplant in a space environment, the following controls would be needed:

1) Hydrogen supply pressure regulator,
2) Oxygen supply pressure regulator,
3) Nitrogen reference pressure regulator,
4) Recirculation flow control,
5) Regenerator bypass valve,
6) Heater controls a) main, b) auxiliary,
7) Radiator (condenser) bypass valve, and
8) Volume compensating bellows.

Since all powerplant testing was run at atmospheric pressure conditions, the nitrogen pressure regulator was not tested on powerplant runs for this program.

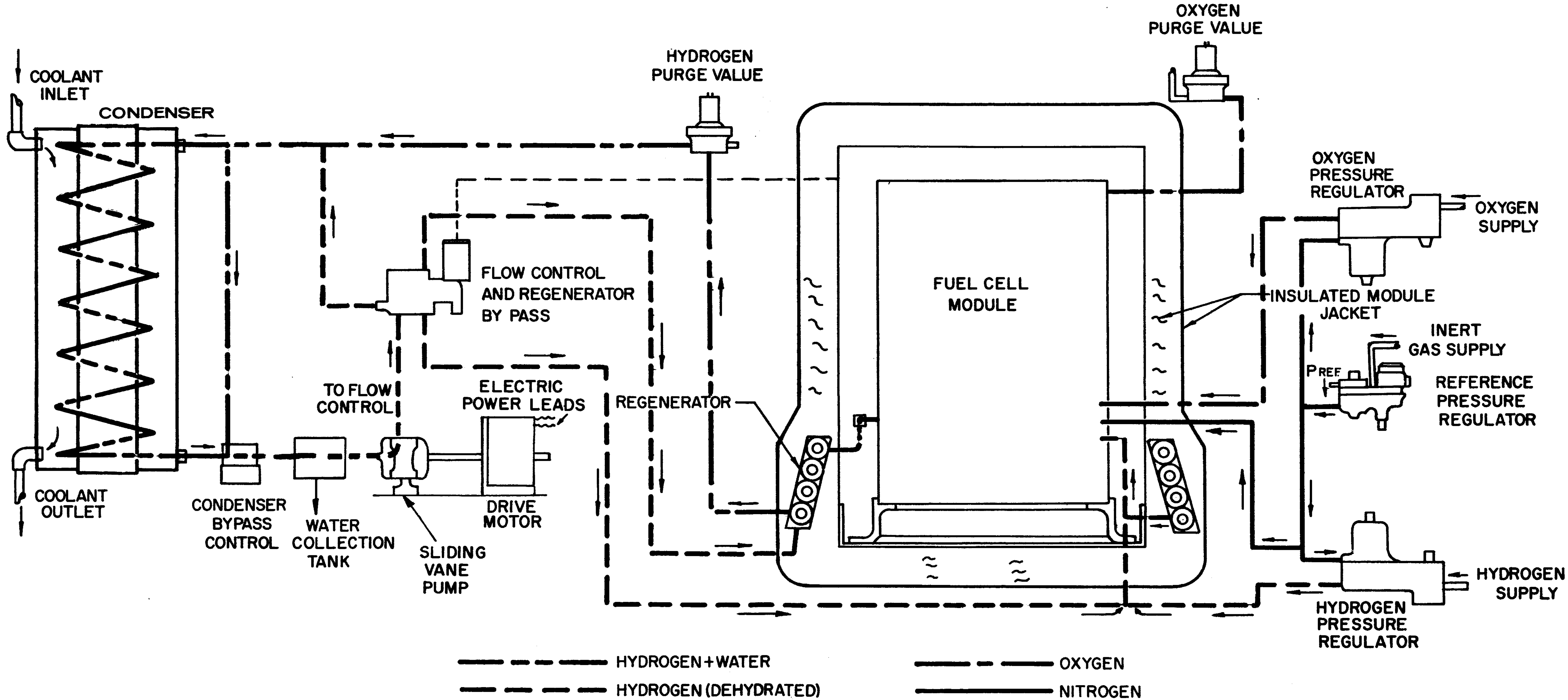
Future fabrication done to support these types of programs should include:

1) Gas supply manifolds for hydrogen and oxygen supply and exhaust gases to be manufactured with ceramic aluminum oxide electrical insulators,
2) Internal Teflon-coated nichrome wire heater mats woven together with Teflon braiding,
3) Full Min-K oven cover and base insulation to test the effect on heat transfer problems and self-sustaining power range, and
4) Flow and regenerator controls with bimetallic elements replacing the present paracymene and bellows system.

Appendix A

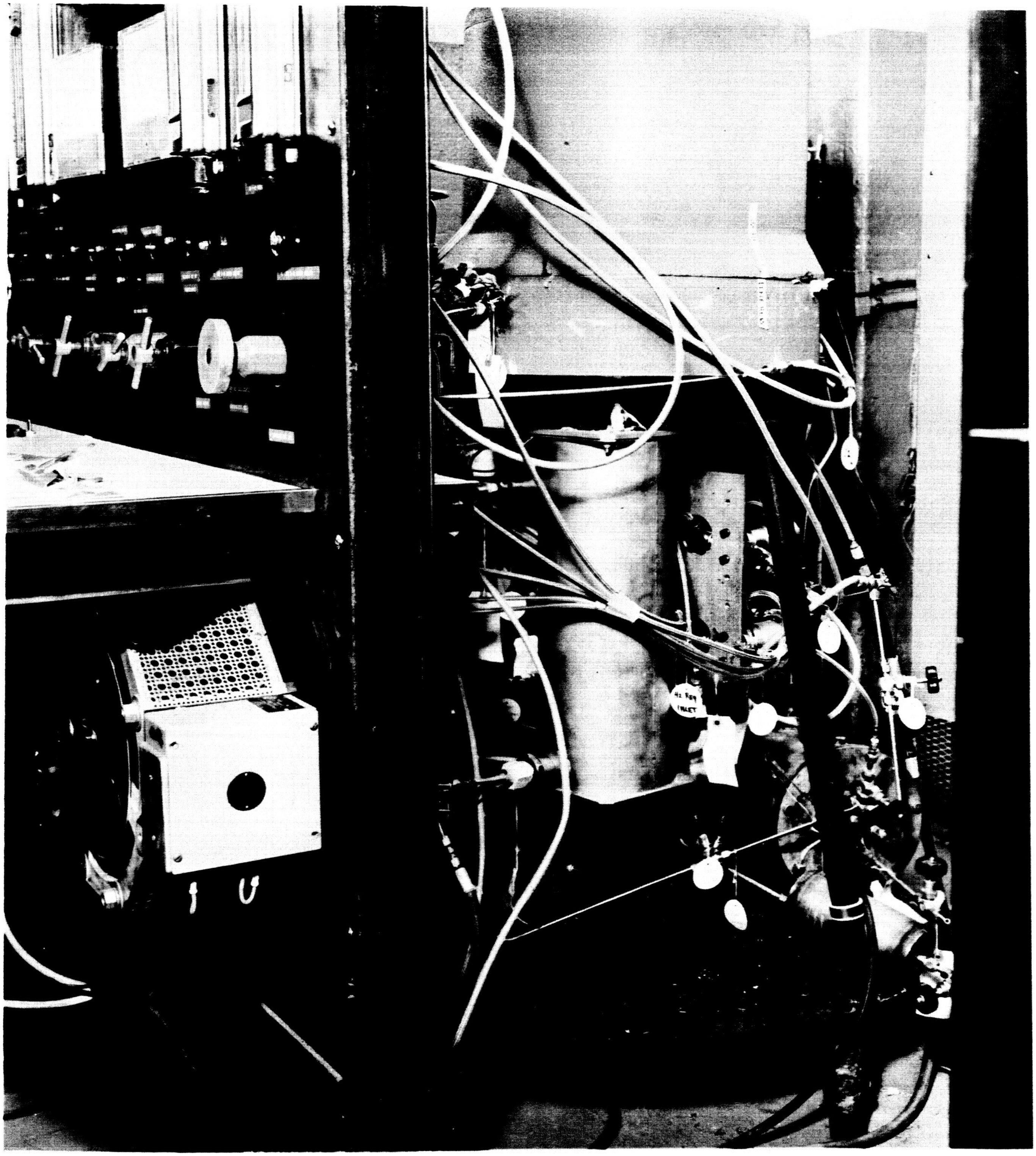
Figures

EXPERIMENTAL FUEL CELL POWERPLANT



PRATT & WHITNEY AIRCRAFT
DIVISION OF
UNITED AIRCRAFT CORPORATION

Figure 1



250-WATT EXPERIMENTAL POWERPLANT INSTALLED IN TEST STAND

XP-12558

Figure 2

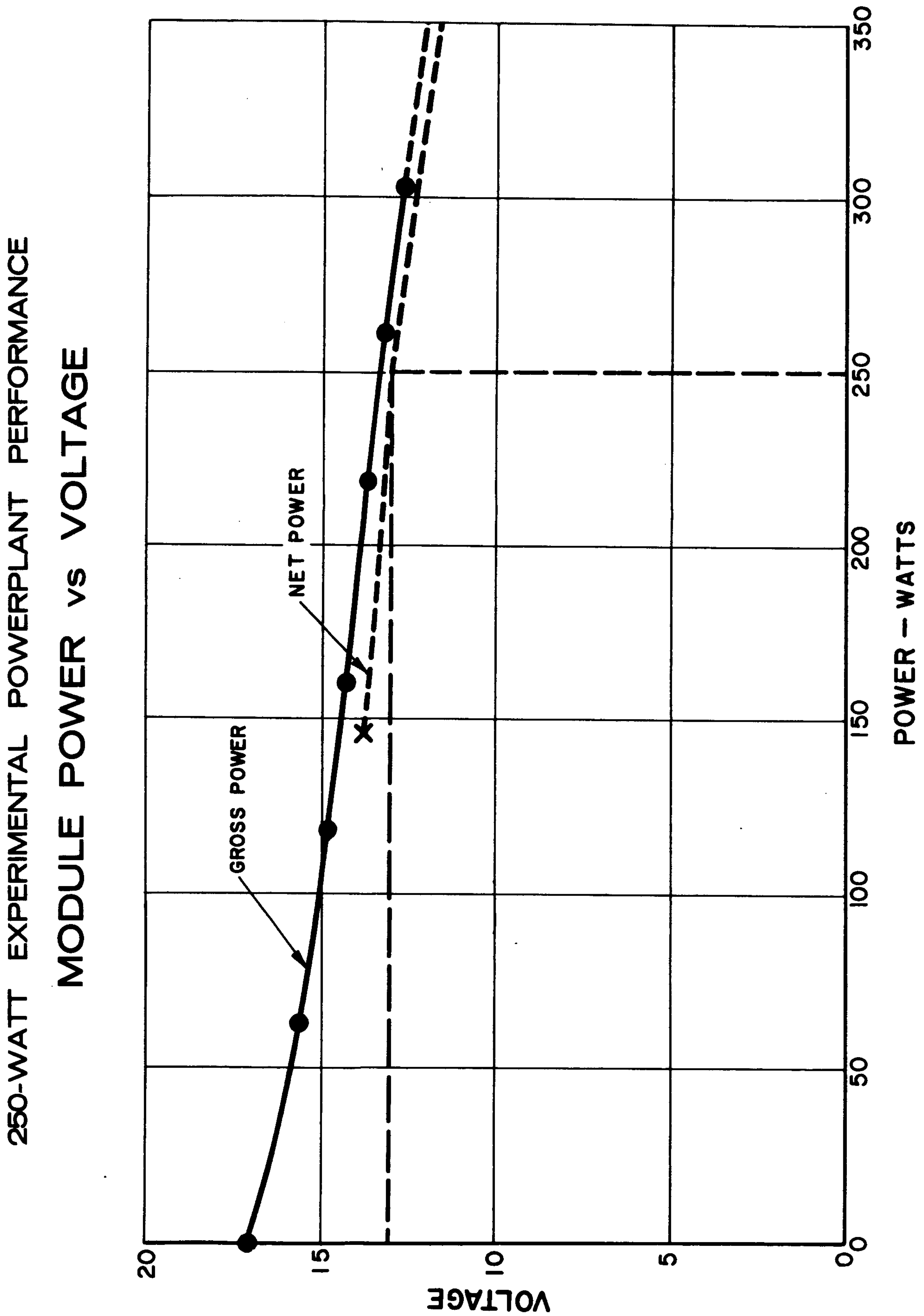

250-WATT EXPERIMENTAL POWERPLANT PERFORMANCE
MODULE POWER vs VOLTAGE
GROSS POWER
NET POWER
VOLTAGE
20
15
10
5
0
POWER — WATTS
0
50
100
150
200
250
300
350

Figure 3

250-WATT EXPERIMENTAL POWERPLANT PERFORFORMANCE

MODULE VOLTAGE vs CURRENT DENSITY

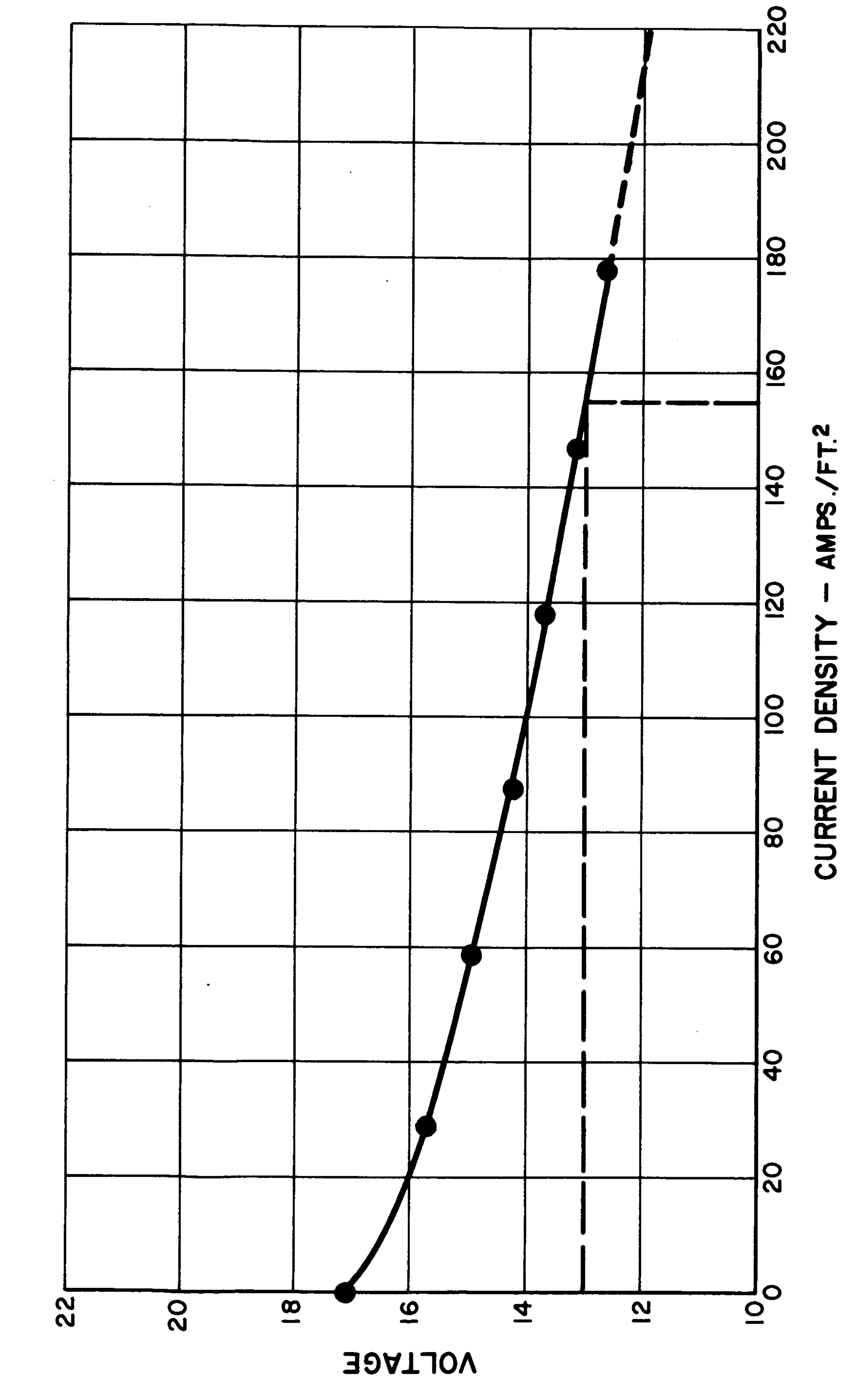


Figure 4

TYPICAL REACTANT PRESSURE REGULATOR PERFORMANCE

SUPPLY PRESSURE = 30 PSIG

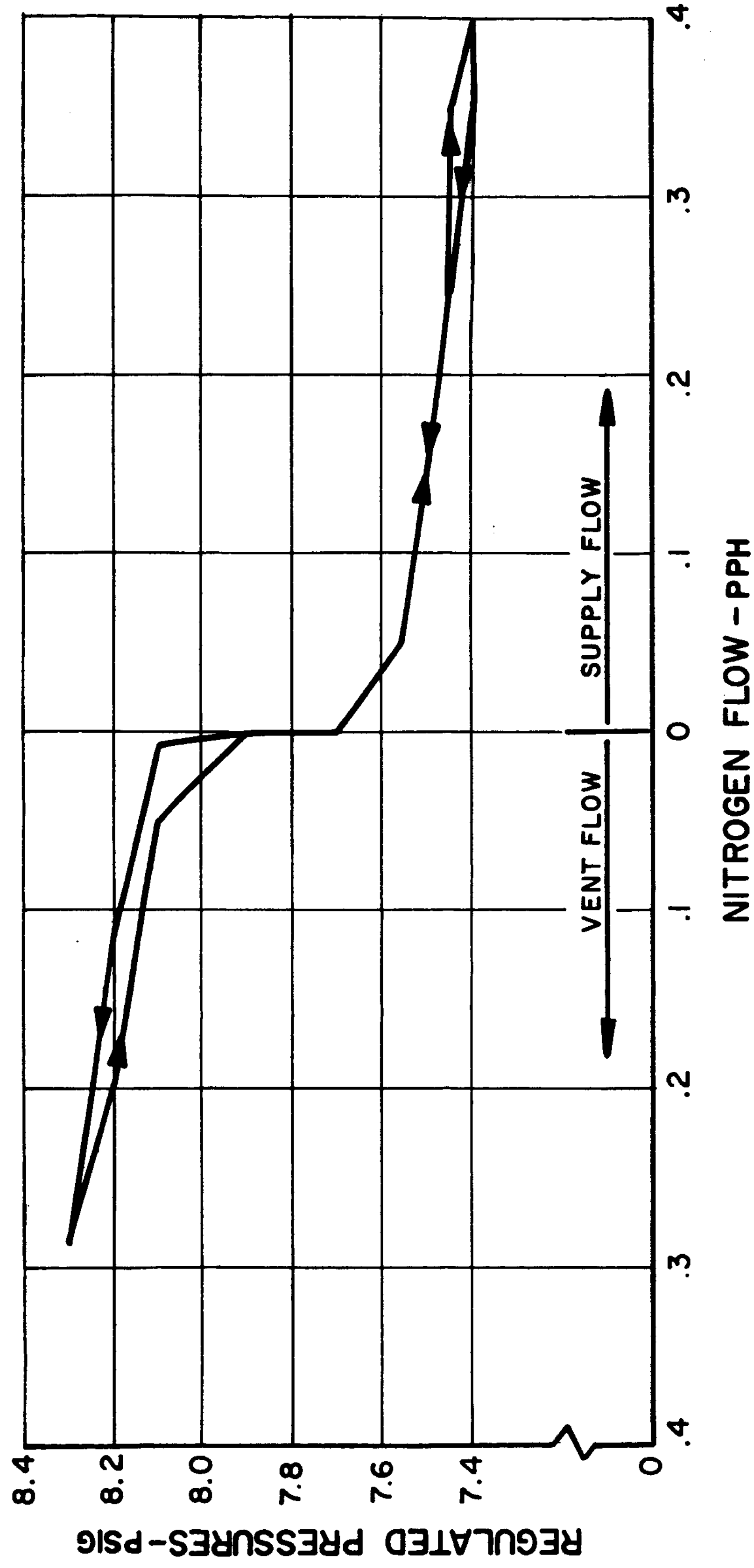


Figure 5

TYPICAL BYPASS CONTROL PERFORMANCE CURVES

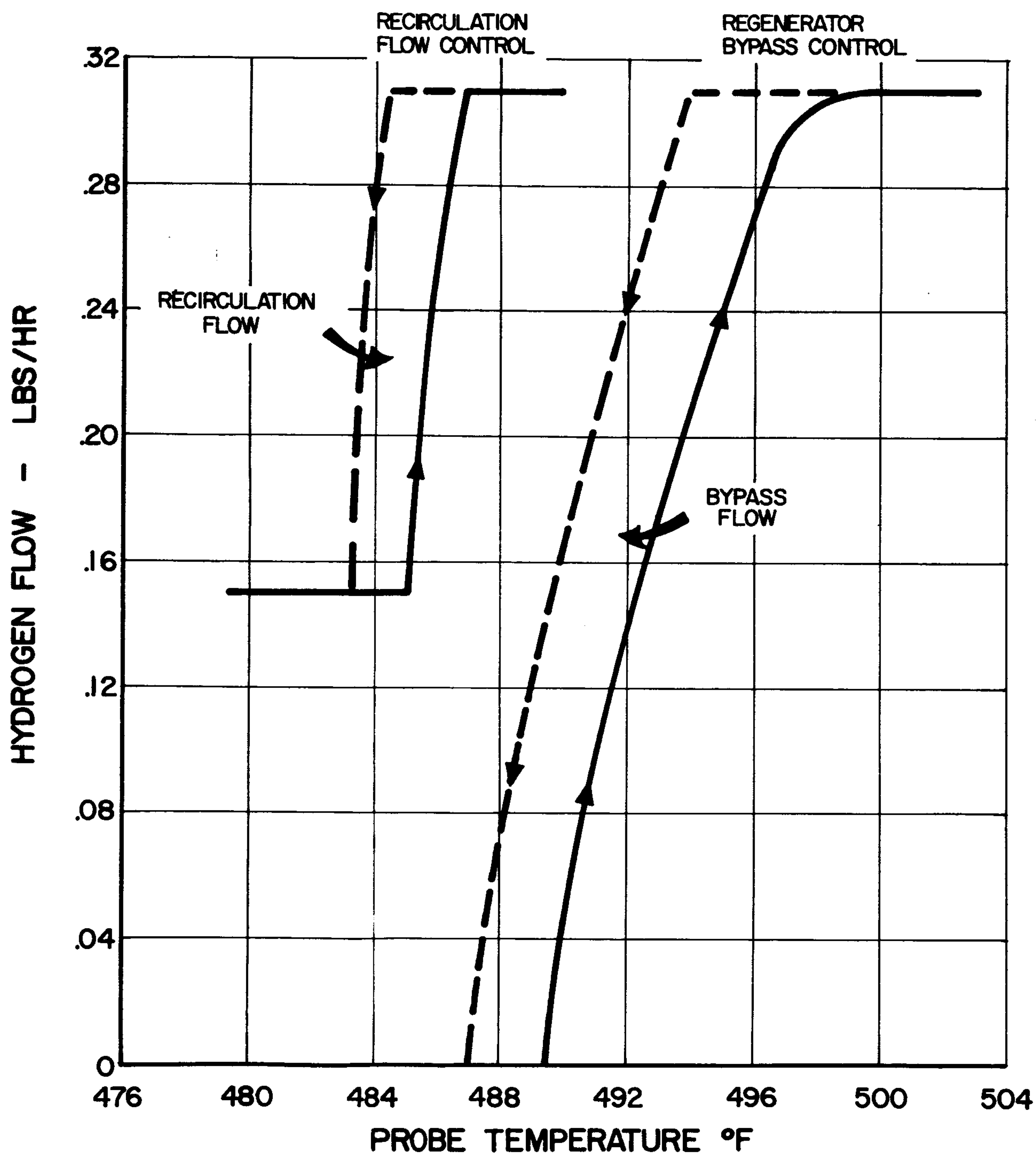


Figure 6

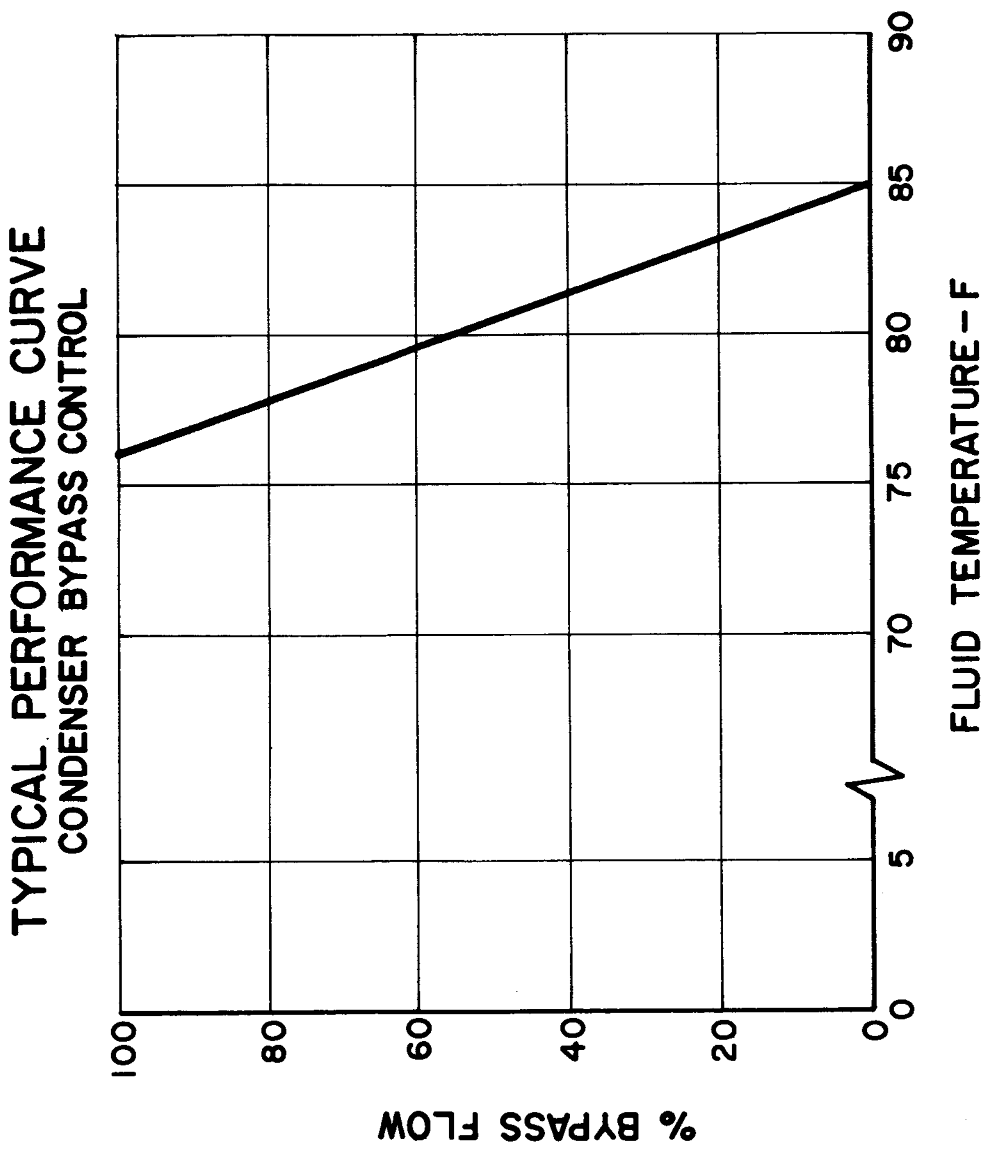

TYPICAL PERFORMANCE CURVE
CONDENSER BYPASS CONTROL
% BYPASS FLOW
100
80
60
40
20
0
0
5
70
75
80
85
90
FLUID TEMPERATURE - F

Figure 7

250-WATT EXPERIMENTAL POWERPLANT PERFORMANCE

MODULE POWER VS. VOLTAGE

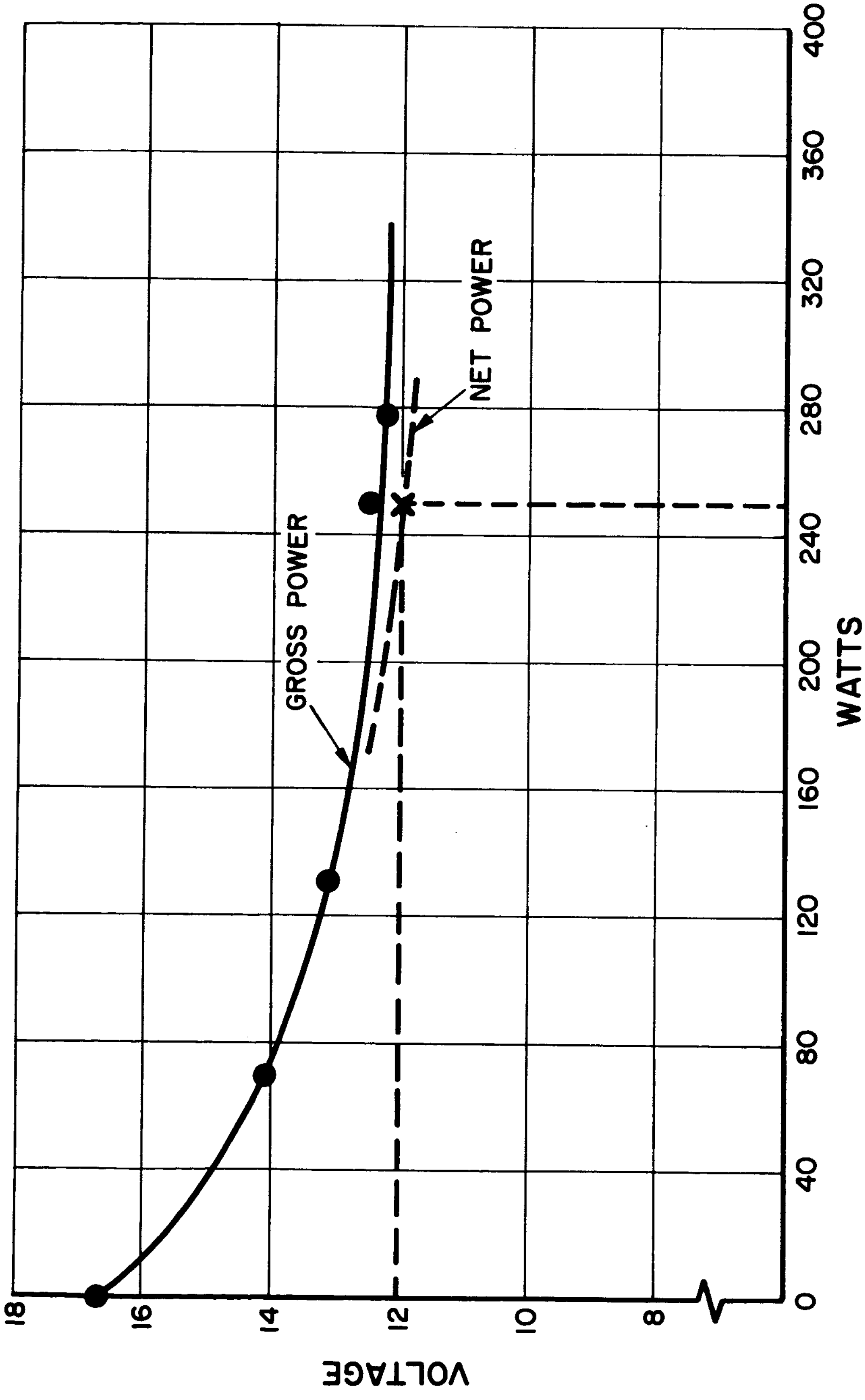


Figure 8

250-WATT EXPERIMENTAL POWERPLANT PERFORMANCE

CURRENT DENSITY VS. VOLTAGE

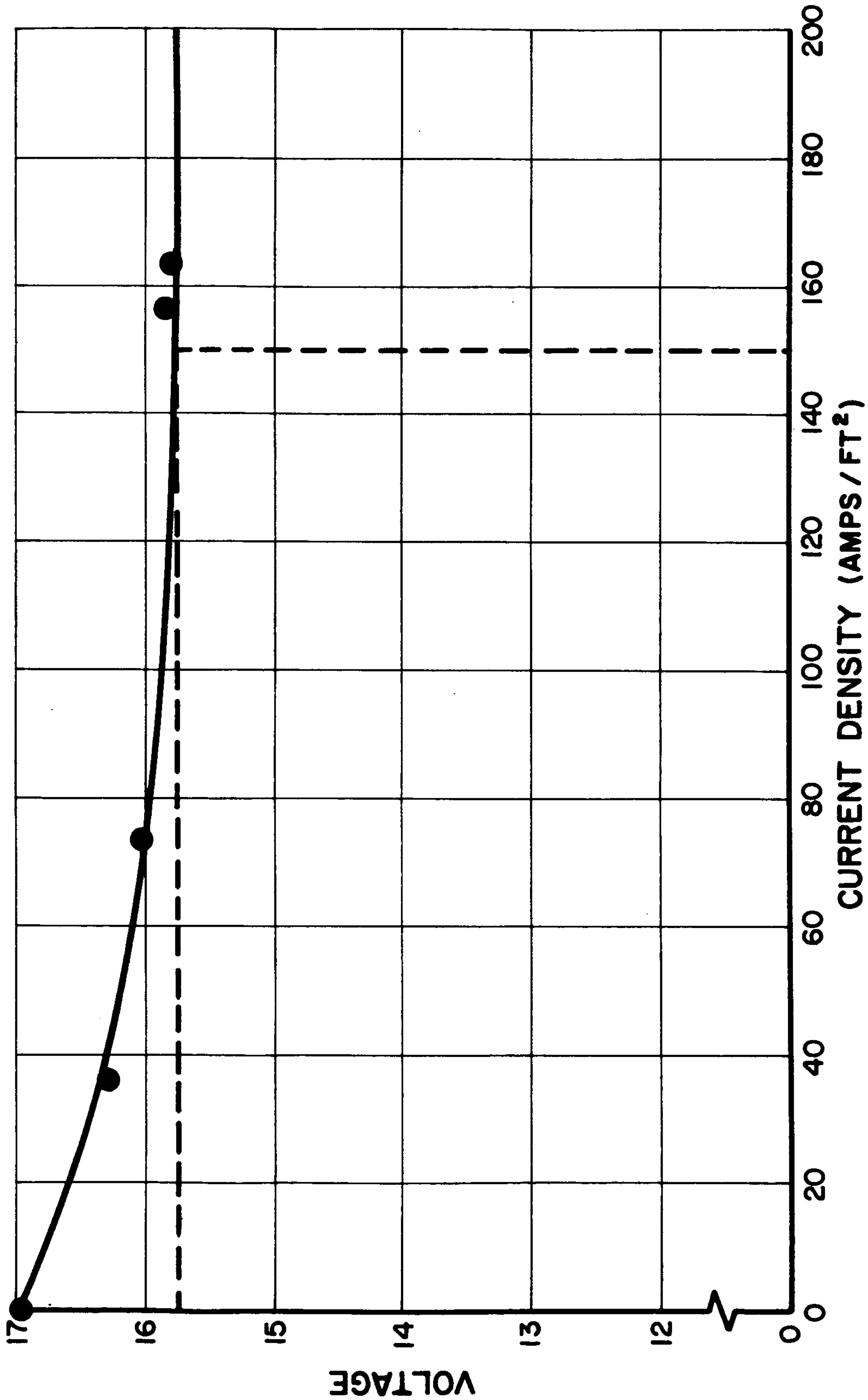


Figure 9

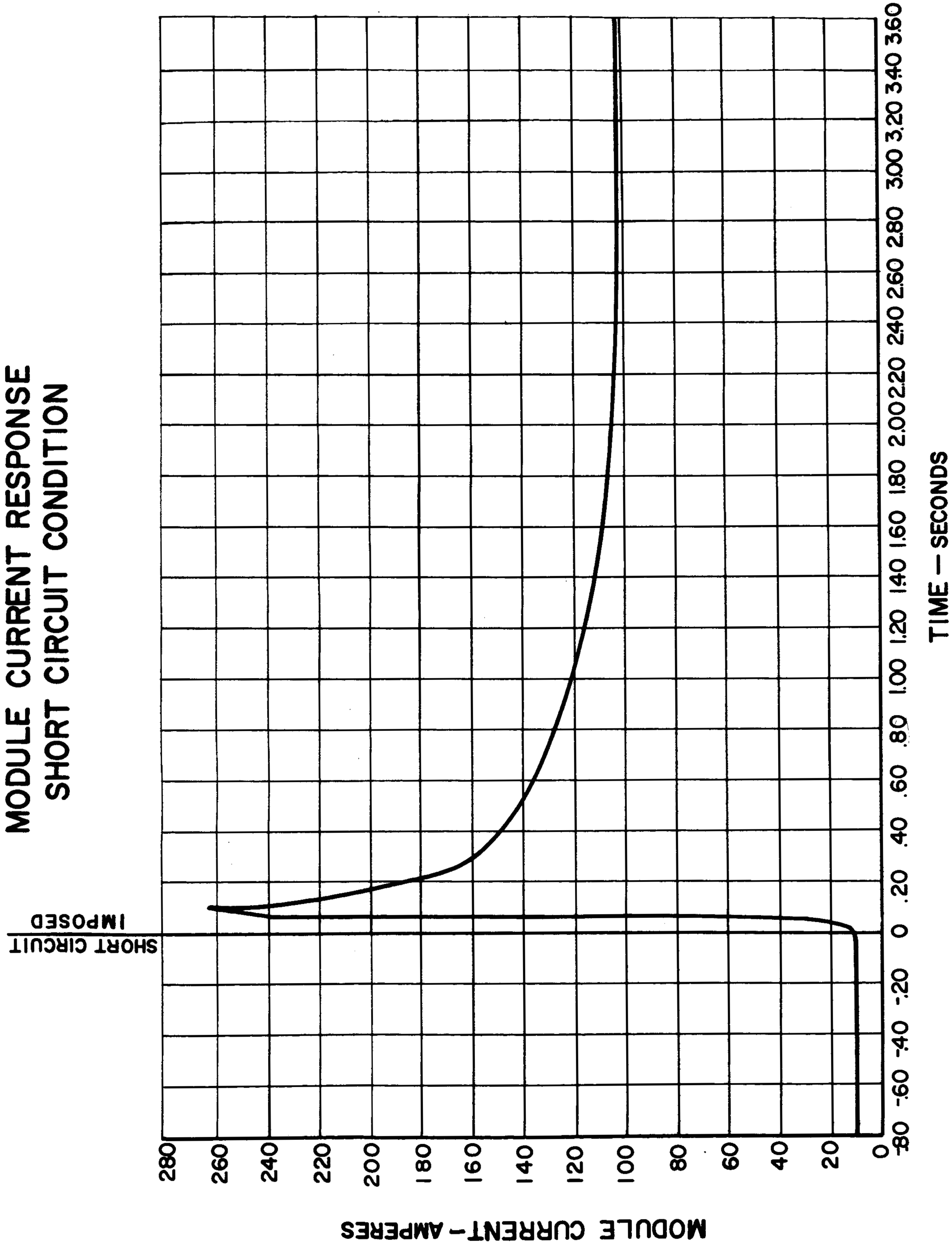

MODULE CURRENT RESPONSE
SHORT CIRCUIT CONDITION
SHORT CIRCUIT
IMPOSED
TIME — SECONDS
MODULE CURRENT - AMPERES
-.80 -.60 -.40 -.20 0 .20 .40 .60 .80 1.00 1.20 1.40 1.60 1.80 2.00 2.20 2.40 2.60 2.80 3.00 3.20 3.40 3.60
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280

Figure 10

MODULE VOLTAGE RESPONSE
SHORT CIRCUIT CONDITION

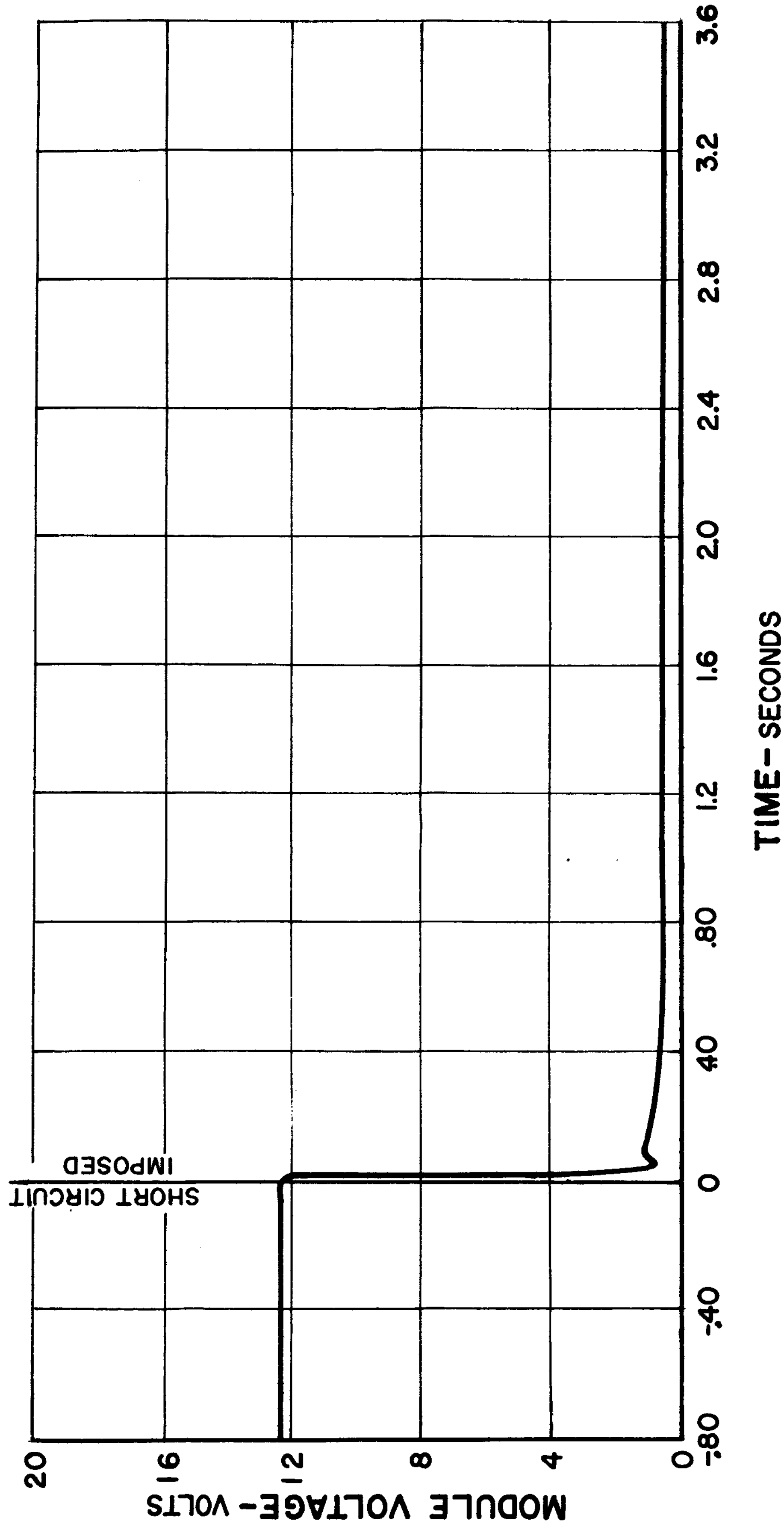


Figure 11