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TOPICAL REPORT

ELECTROCHEMICAL ENERGY STORAGE FOR AN ORBITING SPACE STATION

BY

R. E. MARTIN

DECEMBER 1981

UNITED TECHNOLOGIES CORPORATION
POWER SYSTEMS DIVISION

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS3-21293
TASK I - STATE-OF-THE-ART ASSESSMENT AND PERFORMANCE MODEL

NASA- LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135
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APPENDIX

Alkaline Electrolyte Fuel Cell Development Background

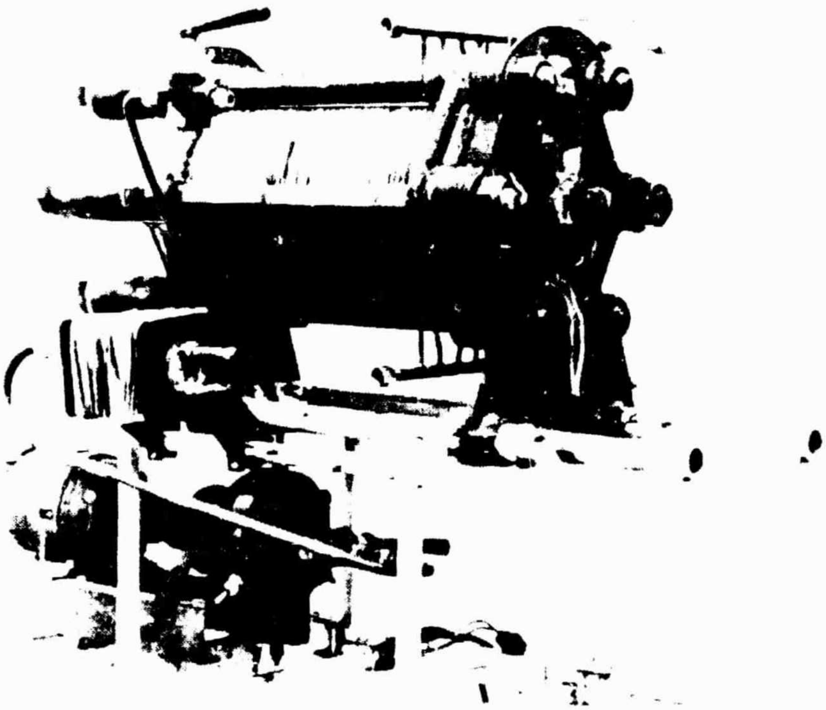
United Technologies has demonstrated reduction to practice for the alkaline technology by the Apollo fuel cell powerplant, Navy underwater fuel cell powerplants, and the fuel cell powerplants for the Space Shuttle Orbiter.

All of these delivery powerplants, Apollo, Space Shuttle and Navy, met firm specification requirements and operated successfully in spacecraft and submersibles.

Apollo

In 1959 United Technologies ran a full-scale power section with Bacon-type cells. The test installation is shown in Figure 19.

400-800 PSI (276-552 N/cm²) 400-500°F (204-260°C)



(FC7086)

Figure 19. Bacon Fuel Cell Stack (1959)

In 1962 the first PC-3A fuel cell powerplants in flight configuration were delivered under the Apollo program. The Apollo fuel cell powerplant was qualified for manned space flight in 1965 and 92 production powerplants were delivered by 1969.

The Apollo fuel cell powerplant is shown in Figure 20. The nominal rating was 1.5 kW at 28 volts with an overload capability of 2.3 kW. The powerplant weighed 241 lbs (109 kg) and was furnished with shock mounts within the cylindrical support skirt. Three PC-3A powerplants installed in the Command and Service Module provided the primary source of electrical power for the Apollo missions.

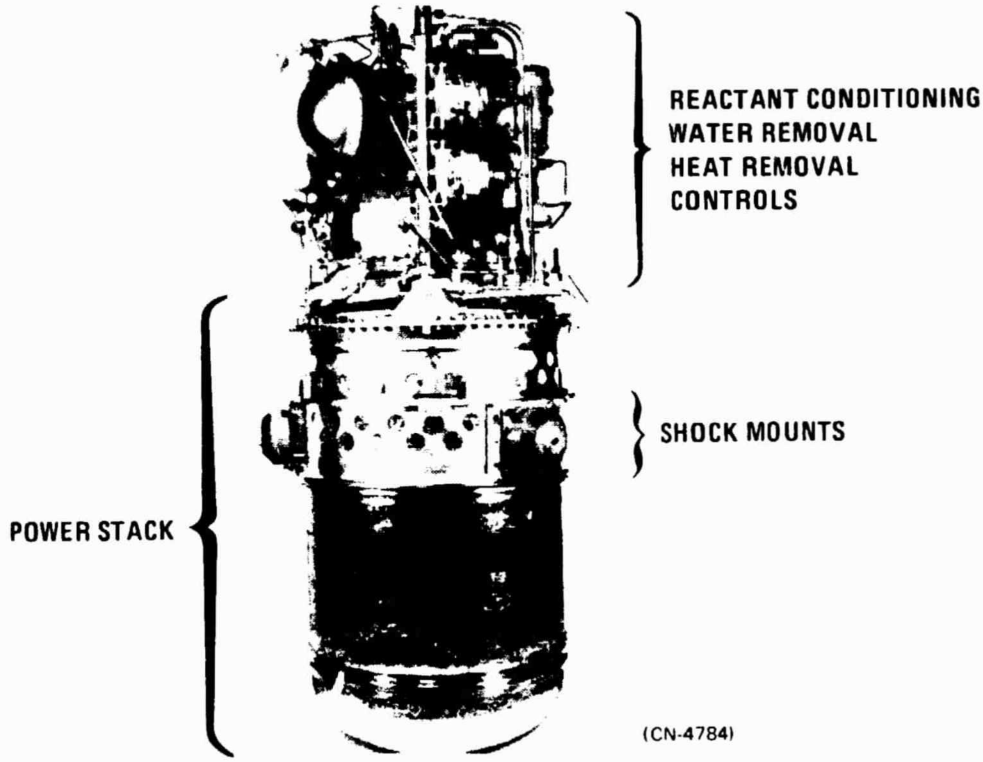
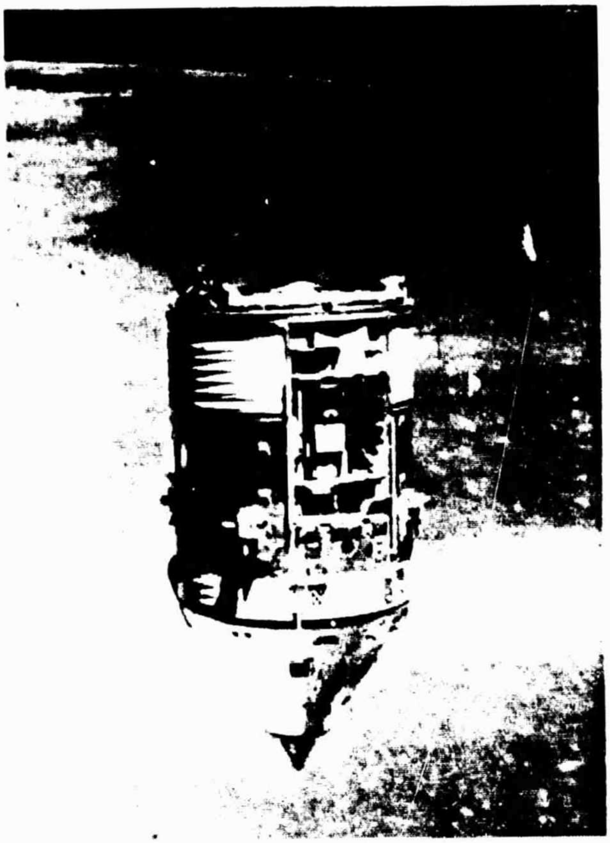


Figure 20. Apollo Fuel Cell Powerplant

The flight experience with the Apollo powerplant is summarized in Figure 21. More than 10,000 hrs of flight time were logged on 54 powerplants during 18 missions during the Apollo, Apollo-Soyuz, and Spacelab programs.



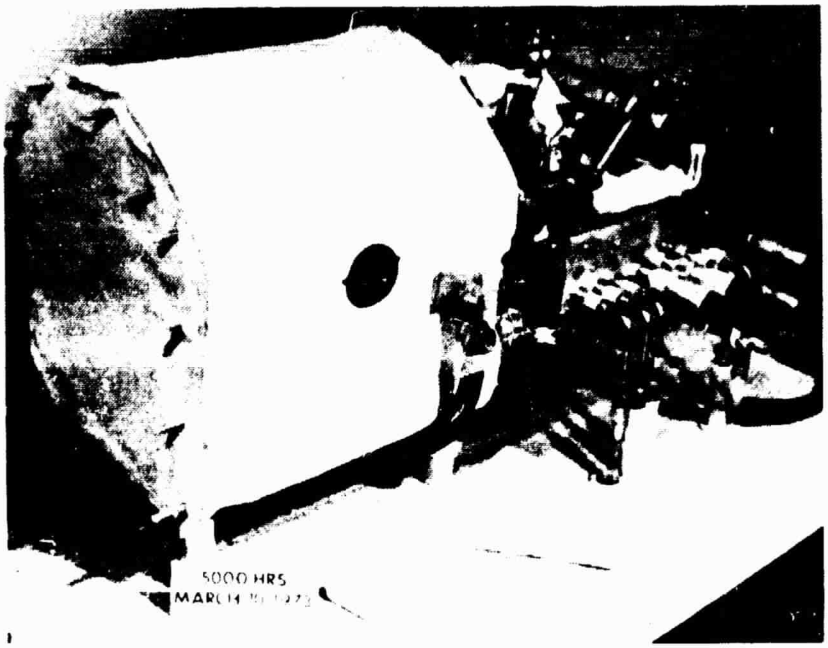
- **PRIME POWER FOR COMMAND AND SERVICE MODULES**
- **18 FLIGHTS INCLUDING:**
  9 LUNAR/3 SKYLAB
  1 APOLLO SOYUZ
- **10,750 HOURS OF FLIGHT TIME**
- **90 POWERPLANTS DELIVERED**

(WCN-1283)

Figure 21. Apollo Fuel Cell Powerplant

Space Shuttle Orbiter Powerplants

The technology for the Space Shuttle fuel cell powerplants was established by the DM-2 powerplant which was developed and demonstrated under a Technology Demonstrator program conducted for the Johnson Space Center. Figure 22 summarizes the results of a 5,000-hr test of the DM-2 powerplant at United Technologies facility. This test includes 31 simulated missions. The powerplant was shut down, cooled down, and restarted for each mission and operated to a variable load profile. The Demonstration started on August 8, 1972 and was completed in eight months on March 10, 1973. No maintenance was conducted on the powerplant during this demonstration. The powerplant was refurbished with a new power section and new bearings in the hydrogen pump and delivered to Johnson Space Center where another 5,000-hour test was completed without maintenance.



- 5072 HOUR TEST TO ORBITER LOAD PROFILE
- NASA-REQUIRED WATER QUALITY FOR ENTIRE TEST
- 21 SELF-ENERGIZED STARTS

(FC7092)

Figure 22. Shuttle Prototype Powerplant Endurance Test

In addition during the DM-2 powerplant program two, six-cell power sections were endurance tested, accumulating 10,000 and 10,500 hours of operation as shown on Figure 23, and a hydrogen circulation pump was tested for 10,000 hours.

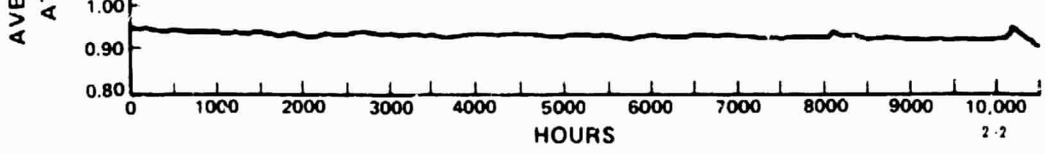
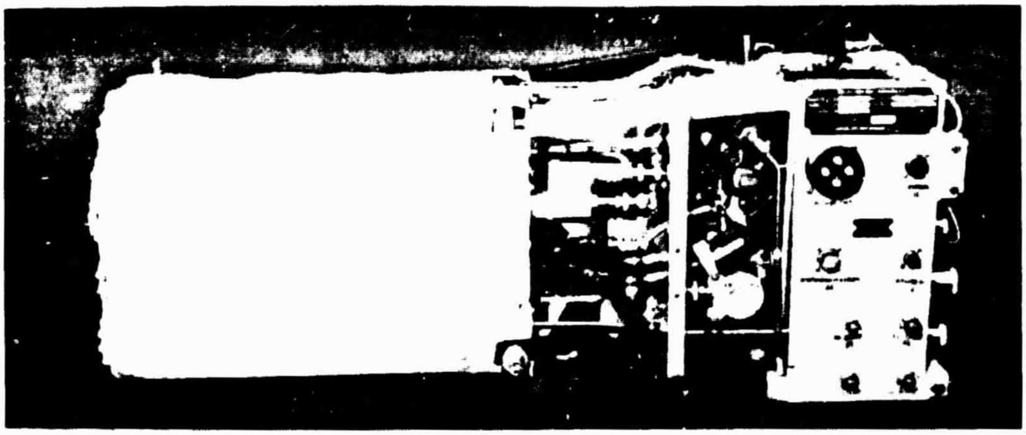


Figure 23. 10,000 Hour Power Section Tests

Three PC17 fuel cell powerplants provide the only source of electrical power on board the Space Shuttle Orbiter.

Figure 24 shows the Orbiter powerplant. The Orbiter powerplant has a nominal maximum power rating of 12 kW with an emergency overload rating of 16 kW. The Orbiter powerplant is smaller than the Apollo powerplant and weights 40 lbs (18 kg) less and delivers eight times the power. The Orbiter powerplant does not require shock or vibration isolation and is hard mounted to the vehicle structure.



(WCN-6742)

Figure 24. Orbiter Fuel Cell Powerplant

The Orbiter fuel cell program started in January 1974. The first development powerplant test started in October 1975. Three development powerplants accumulated 8770 hours of test including accelerated vibration and operation in a simulated space vacuum.

The Orbiter fuel cell powerplant was qualified for manned space flight in June 1979. A 2000-hour qualification test including ten mission cycles and 60 start/stop cycles was completed in January 1980.

Figure 25 is a summary of production powerplants. The three powerplants for the Orbiter Space Craft OV099 were originally delivered in November 1976 for use in the Orbiter Space Craft Enterprise during the Approach and Landing Test Program. These powerplants were refurbished with minor modifications and delivered in October 1980 and have demonstrated five years of shelf life.

- **8 powerplants delivered**
  - **OV 101 FCP's (3)**
  - **OV 101 spare**
  - **Qualification FCP**
  - **OV 102 FCP's (3)**
- **4 powerplants refurbished**
  - **OV 102 spare**
  - **OV 099 FCP's (3)**
- **5 powerplants on order**
  - **OV 103 FCP's (3)**
  - **OV 104 FCP's (2)**
- **1 refurbishment scheduled**
  - **OV 104 FCP**

Figure 25. Production Summary

Service experience with the Orbiter fuel cell powerplant is summarized in Figure 26. A total of 1269 hours have been accumulated on six powerplants installed in the Orbiter Space Crafts "Enterprise" and "Columbia". The service experience includes eight flights during the Approach and Landing Tests from May to October 1977 and the first Orbital flight of STS-1 in April 1981.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

- 1269 HOURS ON 6 POWER PLANTS
- "ENTERPRISE"
  - APPROACH AND LANDING TESTS
    - MAY 1977 TO OCTOBER 1977
    - 8 FLIGHTS
    - 636 HOURS
    - 12 STARTS
- "COLUMBIA"
    - INTEGRATED SYSTEMS TEST – JANUARY 1980
    - FLIGHT READINESS FIRING – FEBRUARY 1981
    - FIRST ORBITAL FLIGHT (STS-1) – APRIL 1981
    - 633 HOURS
    - 3 STARTS

(WCN-6985)

Figure 26. Service History

Navy Powerplants

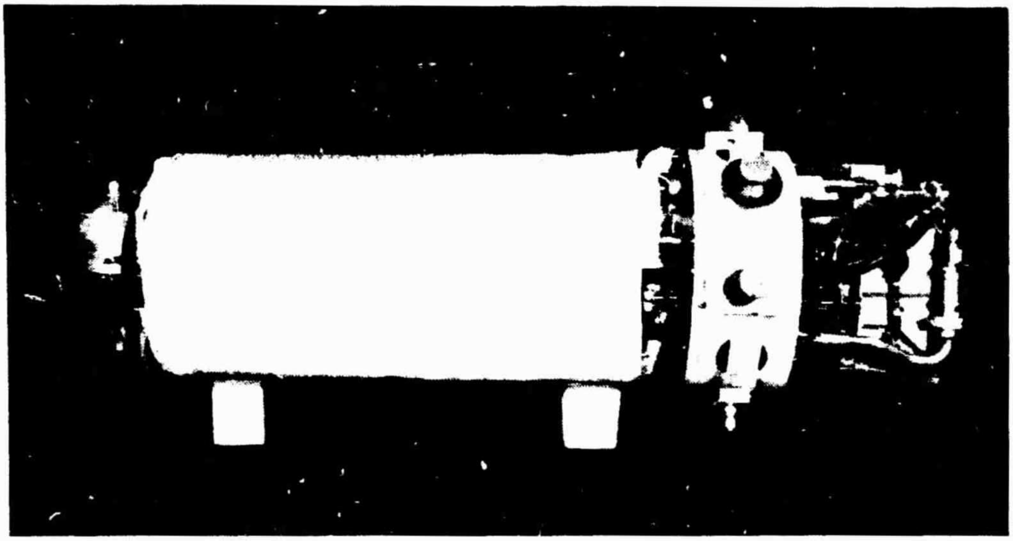
In 1968 the National Academy of Science recommended that the Navy develop hydrogen/oxygen fuel cells for use in energy systems with extended endurance capability in the 1 to 100 kW range.

Studies for the Deep Submergence Search Vehicle conducted for the Deep Submergence Systems Project Office of the Navy established the requirement for a Fuel Cell Power System.

In November 1970, the Navy established a contract with UTC for the design, development, and delivery of a 20 kW 120 volt powerplant. The powerplant was delivered in May 1971 and met all specification requirements.

In 1973 the Navy ordered a 700 kWhr, 60 kW power system for use in submersibles like the Deep Submergence Rescue Vehicle. This system included two 30 kW 120 volt powerplants installed in containment vessels for service at a depth of 5000 feet, a control unit and storage vessels for hydrogen, oxygen and product water.

Figure 27 shows the Navy powerplant and its characteristics. More than 7000 hours of operation were accumulated in development testing and field operation.

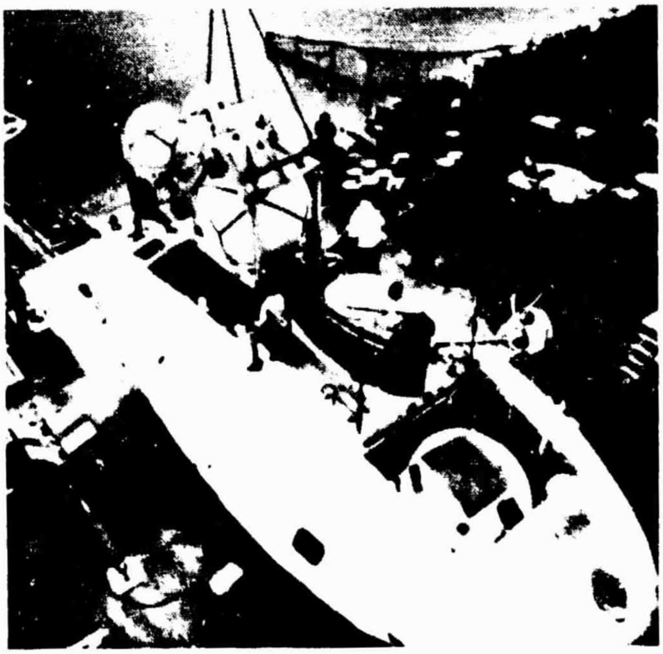


(WCN-2957)

- **POWER SOURCE FOR DEEP SUBMERGENCE RESCUE VEHICLE (DSRV)**
- **TEN POWERPLANTS BUILT**
- **MORE THAN 7000 HOURS OF OPERATION**
- **WEIGHT – 391 LBS**
- **VOLUME – 5.5 FT^3**
- **ENVELOPE – 14" DIA x 72" LONG**

Figure 27. 30-kW Fuel Cell Powerplant

Figure 28 shows the installation of the power system in Deep Quest and a summary of operations. A total of 360 hours of operation was completed during 28 missions in Deep Quest during two periods of operation: August 1979 through January 1980 and April 1980 through September 1980.



- **360 HOURS**
- **22 DIVES IN 10 MONTHS**
  - **SEPTEMBER 1979 TO JANUARY 1980**
  - **APRIL 1980 TO SEPTEMBER 1980**
- **VERIFIED OPERATION AT 5000 FT DESIGN DEPTH**
- **46 HOURS ENDURANCE RECORD FOR SUBMERSIBLES**
  - **550 kWhr WITH NO PURGING**

(WCN-5419)

Figure 28. Operation Submersible "Deep Quest"

In-House Demonstrator Powerplants

The PC8B series of powerplants was developed under in-house sponsored programs to improve upon the Apollo powerplant in the areas of performance, startup characteristics, operating characteristics, endurance and powerplant weight. The PC8B powerplants are shown in Figure 29.

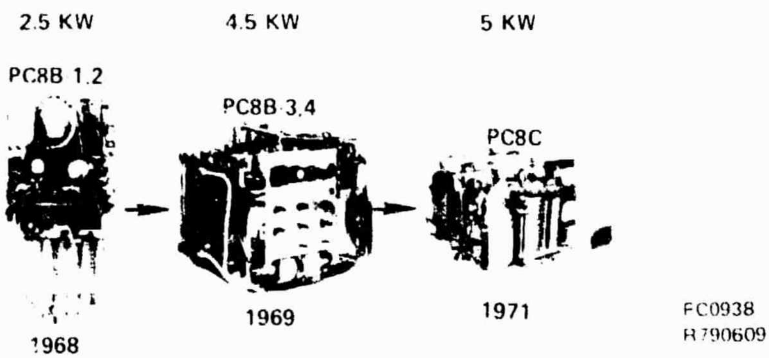


Figure 29. PC8B Demonstrator Powerplants

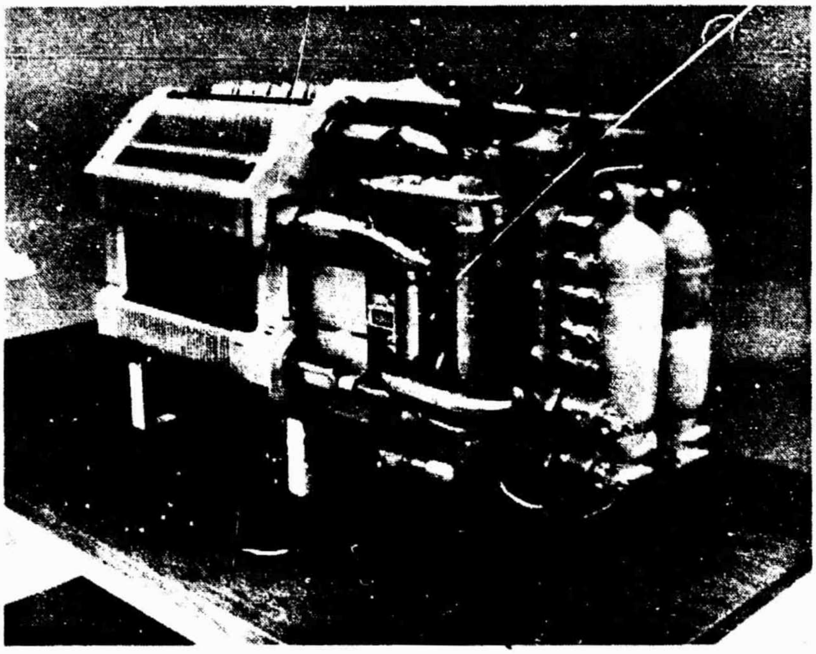
The PC8B-1 was the first powerplant incorporating low-temperature, matrix-type alkaline cells configured for a space application. Cell active area of 0.4 ft^2 (371.6 cm^2) was the same as Apollo. The PC8B-1 retained the Apollo ancillaries and mounting structure. The PC8B-2 was identical to the PC8B-1 except the interface panel and mounting structure were modified for compatibility with the Air Force Manned Orbiting Laboratory.

In 1969, the PC8B was repackaged with a stack of 0.508 ft^2 (471.9 cm^2) active area cells. Designated the PC8B-3, this powerplant was operated as an in-house demonstration unit for more than a year, accumulating 97 starts and more than 6000 hours of reactants. With an improved cooling system, its power rating was raised from 2.5 kW to 5 kW and it was designated the PC8B-4.

The 5 kW PC8C was built in 1971 with a stack of 0.508 ft^2 (471.9 cm^2) active area cells of the high power density type. This cell configuration was developed in the late 1960's in Air Force and internal research and development programs. Originally developed for operation at very high current densities, typically 3000 ASF (3229 mA/cm^2), the cell was found to have superior endurance as well. Endurance testing of this cell configuration in a National Aeronautics and Space Administration Lewis Research Center Program demonstrated over 11,000 hours of operation and a subscale laboratory cell in an internal research and development program exceeded 35,000 hours of testing. This cell configuration has been employed in all subsequent low-temperature alkaline fuel cell powerplants. The PC8C was used as an in-house demonstrator powerplant for nearly two years. During this period it accumulated 100 self-energized starts.

The X712 in-house demonstrator powerplant, Figure 30, was similar to the DM-2 powerplant but incorporated a power section of 36, 0.508 ft^2 (471.9 cm^2) active area cells with a higher performing gold-platinum cathode catalyst replacing the platinum cathode catalyst employed on the DM-2 cell.

X712 has a greater capacity coolant system than the DM-2, giving it a continuous output rating of 15 kW. X712 has been employed as a demonstrator powerplant for four years accumulating 115 self-energized starts.



(WCN-2036)

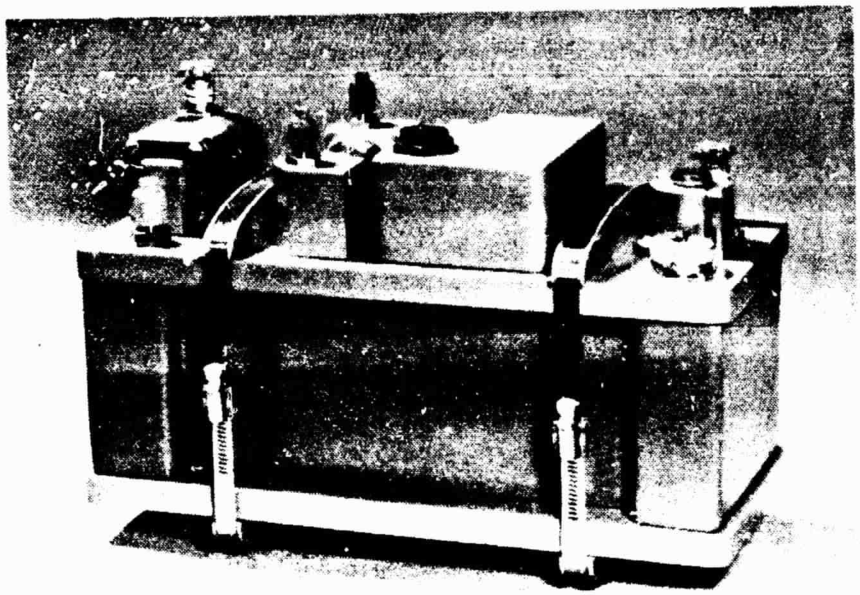
Figure 30. X712 Demonstrator Powerplant

Lightweight Fuel Cell Powerplant

A lightweight 3.5 kW fuel cell powerplant shown in Figure 31 was developed under a program sponsored by NASA-George C. Marshall Space Flight Center. The design is based upon the advanced technology lightweight fuel cell which operates with passive water removal developed under the Lewis Research Center program.

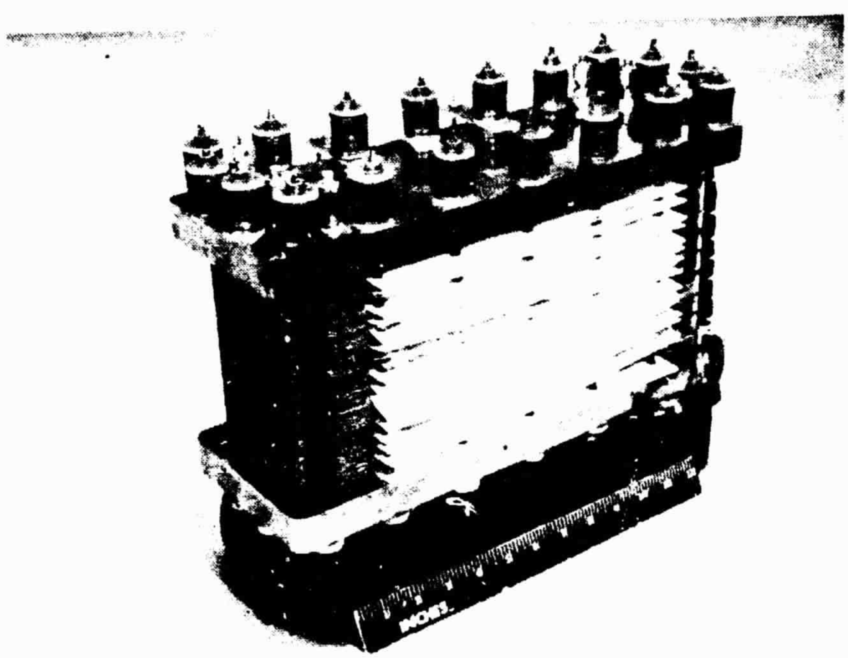
Passive water removal operation eliminates the requirement for a dynamic hydrogen pump water separator thereby allowing a powerplant design with reduced weight, lower parasite power, and a potential for higher reliability and extended endurance. The lightweight fuel cell powerplant design was based upon the requirements of advanced space missions such as Space Tug and Orbital Transfer Vehicle.

The Marshall program culminated in the fabrication of a 24-cell lightweight power section, Figure 32, which has completed a 2000-hour performance demonstration test under the Lewis Research Center Program (reference 1).



(WCN-6336)

Figure 31. Lightweight 3.5 kW Fuel Cell Powerplant



(WCN-7669)

Figure 32. Lightweight Fuel Cell Power Section

Under the MSFC program, over 8,800 hours of endurance testing of two-cell modules, the basic repeating unit of the power section, was completed. These tests confirmed that the lightweight cell design will:

- o Satisfy the 2,500-hour voltage requirement of the Lightweight Fuel Cell Powerplant Design
- o Operate with propellent purity reactants with no significant impact upon cell performance.

A complete summary of the work completed under the Marshall Space Flight Center program is presented in reference 3.

Technology Background

UTC has been conducting an alkaline fuel cell technology advancement program since 1971 under the direction of the Lewis Research Center. This continuing program has identified cell components and a low weight cell design with increased performance and extended life.

- o Developed a lightweight passive water removal cell design with a specific weight of 4 lbs/kW (1.89 kg/kW) compared to the PC17C cell design specific weight of 8 lbs/kW (3.69 kg/kW).
- o Accumulated over 138,000 cell-hours of operation with lightweight passive water removal cell design with one cell operating continuously for 10,021 hours and another cell operating at a current density of 200 Amps/Ft^2 (215.3 mA/cm^2) for 6,680 hours.
- o Demonstrated the increased cell performance and improved long-life stability of the gold-platinum catalyst cathode.
- o Demonstrated the long-life performance stability of the platinum-on-carbon anode catalyst configuration.
- o Confirmed the ability of the alkaline fuel cell to operate in a cyclical mode, representative of a fuel cell-electrolysis cell energy storage system.
- o Identified potassium titanate as a candidate matrix material with the potential to extend cell life.

The work accomplished under the Lewis Research Center program has been reported in references 1 through 10.