D/10 N85-16947

SPACE SHUTTLE ELECTRICAL POWER GENERATION AND REACTANT SUPPLY SYSTEM

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ABSTRACT

A review of the design philosophy and development experience of fuel cell power generation and cryogenic reactant supply systems is presented, beginning with the state of technology at the conclusion of the Apollo Program. Technology advancements span a period of 10 years from initial definition phase to the most recent Space Transportation System (STS) flights. The development program encompassed prototype, verification, and qualification hardware, as well as post-STS-1 design improvements. The review is concentrated on the problems encountered, the scientific and engineering approaches employed to meet the technological challenges, and the results obtained. Major technology barriers are discussed, and the evolving technology development paths are traced from their conceptual beginnings to the fully man-rated systems which are now an integral part of the Shuttle vehicle.

INTRODUCTION

Minimal energy requirements of the earliest spacecraft permitted the use of batteries for electrical power. However, for longer, higher power missions with energy requirements in the hundreds of kilowatthours, the fuel cell has obvious performance and weight advantages which enhance payload carrying capability. During the past 20 years, this potential for better performance and reduced weight has spurred electrochemical technology toward substantial increases in current density (amperes per square foot) and life, with concurrent decreases in specific weight (pounds per kilowatt) (ref. 1) as shown in figure 1. At the same time, increasing fuel cell reactant storage requirements for longer missions and higher energy production rates created a corresponding need for improved performance in reactant cryogenic storage. This need provided the driving force for the development of more sophisticated cryogenic storage techniques (ref. 2). Additionally, the practical application of these systems in advanced spacecraft was contingent upon the availability of necessary component technology for controlling fluid pressures and temperatures, for regulating heat- and mass-transfer processes, and for measuring fluid quantities. These growing requirements motivated significant advances in component technology in both the fuel cell and the cryogenics areas.

One of the most interesting combinations of these technologies is the Space Shuttle fuel cell and reactant supply system, which is the power workhorse and sole primary electrical power source for the Orbiter vehicle (refs. 3 to 5). This system is a highly efficient power generating system that produces electrical power by the electrochemical conversion of hydrogen (H_2) and oxygen (O_2) to potable water. Additionally, the reactant supply system provides breathing oxygen for the crew. This fuel cell and cryogenic system represents a major technological advance over that used for the Apollo missions. The fuel cells used in the Orbiter Columbia's original flights are 50 pounds lighter than and deliver as much as eight times as much power as the Apollo powerplants. A weight comparison to a battery system would indicate that today's advanced batteries would weigh about 10 times as much for the same amount of energy, and weight of the most readily available, or "off-the-shelf," batteries would be as much as 25 times greater than that of this fuel cell/cryogenic system combination. The subsequent addition (effective for the ninth Space Transportation System flight (STS-9)) of a third substack of cells to each Orbiter powerplant further improves the specific weight picture and assures a lifetime 10 times greater than that of the Apollo powerplant. The Shuttle reactant storage tanks are essentially scaled-up Apollo-type tanks, but they are far superior to the Apollo tanks in that they contain significantly improved insulation and support schemes. Moreover, the reusability of the tanks and the technical challenges thereby presented are particularly important for this paper (ref. 6).

Accordingly, in this report, the status of the fuel cell and cryogenic technologies at the conclusion of the Apollo Program is summarized, and the predevelopment technology activity which contributed substantially toward the formation of a firm technology basis for the Space Shuttle Program is discussed. Relevant technology issues are investigated, and the most significant innovations are noted. The manner in which the lessons learned from Apollo and pre-Shuttle technology programs were directly applied to the Shuttle development program is shown. Finally, major achievements in the test and evaluation programs supporting Orbiter development are discussed, and flight experiences are described.

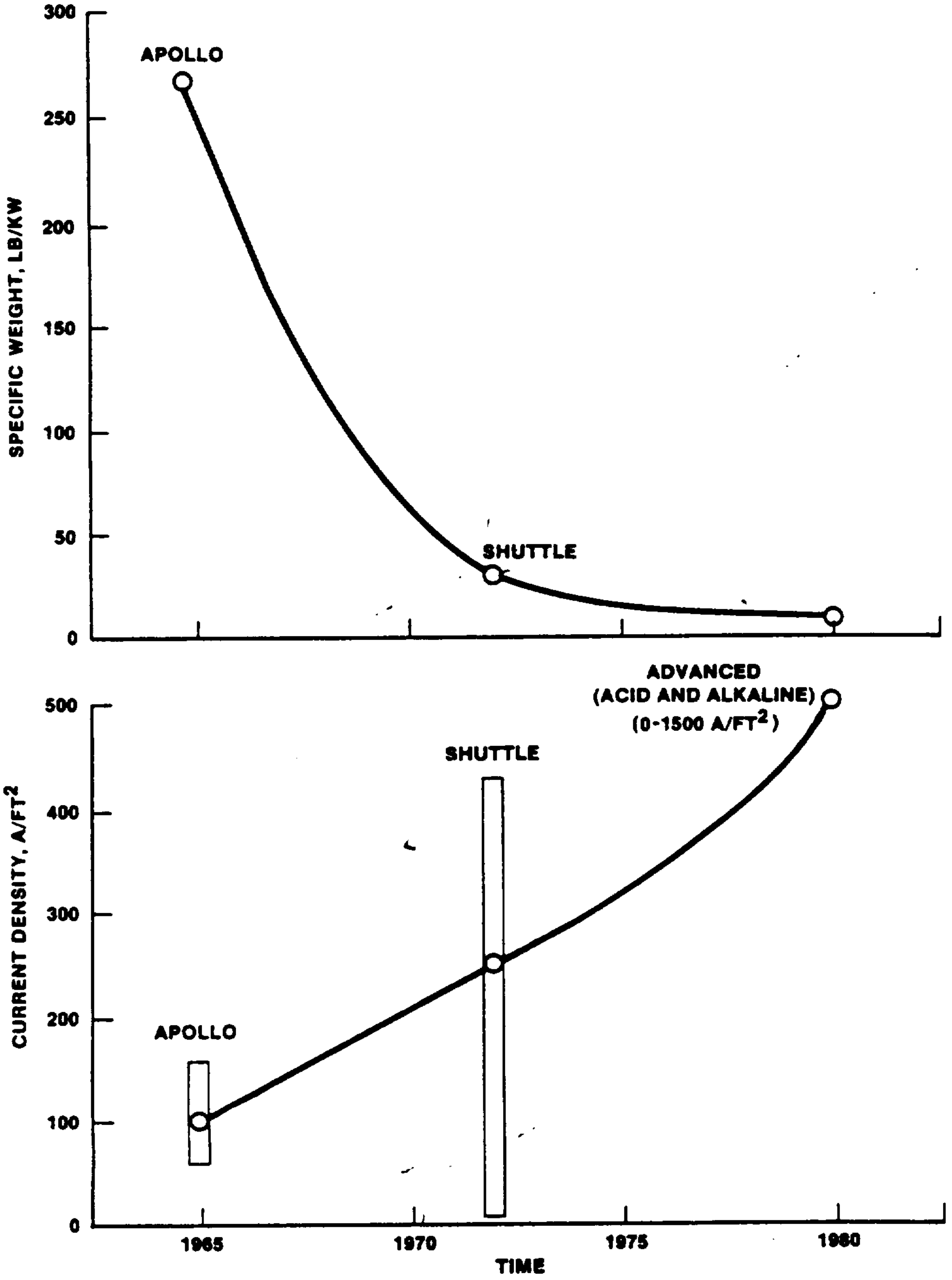


FIGURE 1.- NASA FUEL CELL TECHNOLOGY ADVANCES.

BACKGROUND

STATE OF TECHNOLOGY AT APOLLO PROGRAM CONCLUSION

The end of the Apollo Program marked the achievement of significant milestones in the development history of fuel cell power and cryogenic reactant supply systems. The flight-proven Apollo system could generate electrical energy at the rate of approximately 2 kilowatts for 14 days, with an available peak power of more than 4 kilowatts for limited periods of time, while supplying potable water and metabolic oxygen for a crew of three. This system consisted of three fuel cell powerplants of the Bacon cell technology, with accompanying supercritically stored hydrogen and oxygen reactants.

In the early 1960's when it was chosen for Apollo, the technology state of this fuel cell concept was extremely low, and many developmental difficulties were encountered from the beginning of the program (ref. 7). Although many of these problems were solved, some were merely "fixed" using workaround techniques because of the pressing schedule. This approach resulted in many inherent system design difficulties and features which made the fuel cell sensitive to operator error and necessitated the use of more complicated operational procedures than desired.

Initially, problems were encountered with pressure sealing in the 500°-F potassium hydroxide (KOH) environment. Also, a lightweight, long-life pump and water removal system which would operate satisfactorily in a 60-psi, 200°-F wet-hydrogen environment was needed. A highly reliable low-power coolant pump which could function well in a thermal vacuum environment at temperatures from -40° F to 140° F also had to be developed.

Contamination and corrosion in fluid flow loops with critical hardware tolerances were serious problems for many spacecraft systems and the fuel cell was no exception, as evidenced by sluggish valves and pumps failing to start. These difficulties were overcome mainly by improved servicing and operational procedures; material or design changes (or both) were made when there was no other means of dealing with the problem. Other problems with valves, accumulators, cell separation, and internal cell shorting were met and dealt with during the component development, production, and ground test phases of the program. As the production phase of the program was begun, a new set of problems evolved. Careful attention was needed in areas of process control, servicing, spares production, and traceability to ensure reliable flight-qualified hardware.

Although the actual Apollo space flights were relatively free of fuel cell failures, two classic fuel cell problems discovered in flight are worthy of note. The first involved air and particulate contamination trapped in the coolant system in the normal-gravity servicing environment. In low- or null-gravity conditions, the gas and particles freely migrated through the fluid loop and resulted in coolant pump cavitation and reduced thermal control capability. Improved servicing procedures precluded recurrence of the problem in later flights. The second problem involved condenser exit temperature oscillations occurring first in lunar orbit and found to be caused by a low-gravity, two-phase flow instability manifested only under certain powerplant operating conditions. Complex mathematical models and extensive in-house testing were required to characterize the instability and to quantify the operating conditions at which it occurred, so that valve schedule changes could be devised to accommodate this idiosyncracy of the system (ref. 8).

At the end of the Apollo Program, a much improved cryogenic reactant storage system over the one originally conceived was seen, partly because of the Apollo 13 oxygen tank failure (ref. 9). Although low-gravity, two-phase fluid handling problems were avoided through the use of supercritical storage, development problems occurred early in the Apollo Program with insulation, heaters, pressure vessels, fans, and other components (ref. 10). These difficulties were resolved largely through design modifications and changes in hardware suppliers, and through tighter control of manufacturing processes, techniques, and quality. Other problems that developed during the flight phase required some redesign and requalification of flight hardware, but, overall, the state of technology in supercritical cryogenic storage supply dewars was advanced significantly during the Apollo years.

In the area of dewar insulation, significant design innovations involving multilayer insulation schemes with an embedded vapor-cooled shield were introduced during Apollo. Early insulation schemes were completely load-bearing, but excessive heat leak led to the use of semi-load-bearing insulation straps encircling the hydrogen pressure vessel and contacting the pressure vessel at specific points where the load is transmitted to a girth ring.

Apollo heater design schemes started with an original static heater concept and settled on a fan and heater combination which reduced system weight and minimized fluid stratification. After the Apollo 13 incident, the fans were deleted from the oxgen tanks, and the performance of the resulting static fluid heaters depended to a large extent on the effective gravity level.

Early pressure-vessel problems with the hydrogen tanks involved vessel failures due to room-temperature creep in the titanium alloy (5 Al-2.5 Sn), titanium hydride formation, and resultant spalling which caused vent-disconnect weld failures, and to problems encountered in the electron-beam welding process. Resolution of these problems was accomplished by changes in materials and fabrication processes, and by improved weld specifications and quality control, including the use of a borescope for weld inspection.

Major advances in the technology of other cryogenic components were seen by the end of Apollo. Included were significant improvements in fan motor design and the development of better vacuum potting techniques for the vac-ion pump package to prevent electromagnetic interference (EMI) and corona effects.

Three significant failures associated with the cryogenic storage system during Apollo had an impact on the technology base. These were failure of the automatic pressure control system in a hydrogen tank (Apollo 9); loss of vacuum in a hydrogen tank annulus, detected during loading (Apollo 12); and, of course, the Apollo 13 incident in which an oxygen tank failed in translunar flight. Through a diligent effort on the part of the Apollo team, a successful recovery from each of these failures was effected. Thus, at the end of the Apollo Program, significant technological improvements were seen in cryogenic system design, particularly in pressure-vessel fabrication and welding, bimetallic joints, vapor-cooled shields in high-performance insulation, vacuum acquisition and retention, EMI control, and metallurgical techniques.

In addition to the numerous system hardware technology advances, much progress was made in the development of analytical modeling techniques for electrical power and cryogenic storage systems (refs. 11 to 14). Also, certain advances in electronics technology were ready for application in future power systems. Collectively, these achievements constituted a firm technology base from which the Space Shuttle development program could begin.

RELEVANT TECHNOLOGY PROGRAMS PRECEDING SHUTTLE

Although the Apollo system was satisfactory for its intended use, it nonetheless left much to be desired as a means of power generation for future spacecraft. Even as far back as the days of Apollo, the NASA Lyndon B. Johnson Space Center (JSC), with awareness of the limitations of the Apollo fuel cell design, initiated technology development programs using NASA Office of Aeronautics and Space Technology (OAST) funding with both the Allis-Chalmers Manufacturing Company and the General Electric Company (GE). At that time, Allis-Chalmers was advancing the alkaline capillary matrix concept, which held the promise not only of longer life but also of alleviating the severe operational constraints experienced with the Apollo design. General Electric, on the other hand, was continuing development on an early version of the acid solid polymer electrolyte (SPE) fuel cell. The Allis-Chalmers concept was ultimately selected to be developed for the Orbital Workshop in the NASA Apollo Applications Program (AAP) and for the U.S. Air Force Manned Orbiting Laboratory (MOL). Later, the MOL program was canceled, and the Orbital Workshop concept was restructured and renamed Skylab. At this point, for economic reasons, a programmatic decision was made to use existing Apollo fuel cells for Skylab. These two events led to the curtailment of all Allis-Chalmers fuel cell activities. The Power Systems Division (PSD) of United Technologies Corporation, in recognition of the Apollo design limitations, had also been developing the alkaline capillary matrix technology, which has become its mainstay for the Shuttle fuel cell. Meanwhile, a technological breakthrough involving reactant prehumidification in the GE fuel cell made it a viable option for the projected Shuttle Orbiter power system.

During this same time period, the Bendix Company had been chosen to build cryogenic storage tanks for the Orbital Workshop and the Garrett AiResearch Corporation was selected to provide tankage for the MOL. However, cancellation of both these programs halted this effort before any significant technology advancements were realized.

By the close of the decade, although technological progress had been achieved in both fuel cells and cryogenic storage, much of it was fragmented and affected heavily by programmatic decisions outside the realm of these technologies. It was thus recognized in early 1970 that for the Space Shuttle, additional technology improvements would be required. For this reason, JSC initiated a competitive procurement activity with United Technologies Corporation and GE aimed at upgrading the state of hydrogen-oxygen fuel cells for Shuttle needs (ref. 15). Additionally, two technology programs for advancing the state of the art in cryogenic oxygen and hydrogen storage vessels were begun by JSC with the Beech Aircraft Corporation, Boulder Division: the Oxygen Thermal Test Article (OTTA) and the Hydrogen Thermal Test Article (HTTA) programs (refs. 16 and 17). At this time in the early Shuttle conceptual definition, a cryogenic orbital maneuvering system (OMS) was being considered; therefore, the vessels were sized for both OMS propellants and power reactants, as well as for metabolic oxygen. These programs brought about such improvements as silver-plated H-film insulation, S-glass support straps, and a refined vapor-cooled shield. Concurrently with these fuel cell and cryogenic technology programs, JSC also initiated a cryogenic supply system optimization study, one of the principal objectives of which was to investigate the feasibility of a totally integrated cryogenic fluid storage and supply system for the Orbiter that would provide fluids for propulsion, power generation, and life support (ref. 18). After selection of the present solid rocket booster/external tank combination in lieu of the all-cryogenic Shuttle, this activity was reoriented to a cryogenic cooling study. Perhaps the most useful result of this work was the establishment of a comprehensive data base for cryogenic system component design. This information was used extensively in the design and development phase of the Shuttle reactant supply system.

TRANSITION TO THE SHUTTLE ERA

GREATER DEMANDS THAN APOLLO

With the refocusing of the space program to near-Earth orbit following the lunar exploration phase, plans emerged for larger crews and increased activities with experiments and other flight hardware. Thus, electrical power requirements increased by more than an order of magnitude over the modest levels of previous programs and produced greater demands for high-performance power generation systems. With the emphasis on economy, this objective could only be attained through extended life and reusability. The concept of reusability required high operational tolerance and flexibility to achieve acceptable turnaround rates at launch and landing sites. Furthermore, to optimize total vehicle design, plans were laid for an increase in system integration for the Shuttle compared to previous spacecraft. Taken all together, these increased demands pointed up the requirement for a quantum jump in technology over that of the Apollo Program. Fortunately, these needs had been recognized earlier by fuel cell and cryogenic storage technologists and by the NASA OAST, and technology development in both areas had been evolutionary, building up from modest levels beginning just after the Apollo design was frozen in the early sixties to the competitive technology programs of the seventies resulting in the selection of the present Shuttle system. Through these programs, major technological barriers were overcome and the fuel cell and cryogenic storage system was placed in the enviable position of being one of the few systems truly ready, from a technology standpoint, for the development program. The development effort was reduced to solving engineering problems, though not at all insignificant, for which no major scientific breakthroughs were required. This state of technological preparedness earned for the power generation and reactant storage system the distinction of being the only subsystem which reached the end of the originally defined Shuttle development program on schedule and within the allocated budget (ref. 19).

LESSONS LEARNED FROM PREVIOUS PROGRAMS

The completion of JSC's competitive fuel cell technology programs in 1973 marked the end of a decade of significant accomplishments in fuel cells and cryogenic storage, and it was a time for reflection by the technical community on the successes and failures of these programs during that brief period before the Shuttle development program began. In retrospect, two things were clear to the fuel cell and cryogenics experts who were to be involved in the Orbiter project: (1) the features of a power generation and reactant storage system that were to be avoided in the Orbiter design were known from the Apollo Program and (2) technical risks in the development program could be minimized by using certain techniques and ideas which had evolved from the technology programs. Most unworkable methods had by this time been eliminated, and feasible techniques had been found, for the most part, to achieve the Orbiter goals of increased life, higher power, improved operational flexibility, and lower specific weight and volume.

Two fuel cell approaches were successful: the PSD fuel cell, with its improved alkaline electrolyte matrix, and the GE fuel cell, with its acid solid polymer electrolyte and hydrogen prehumidifier. Both of these concepts had undergone significant improvements during the competitive technology program, and engineering models of each had been subjected to a 5000-hour test program, with small stacks (four to six cells) and other components accumulating more than 10 000 operating hours.

Cryogenics specialists had reached a similar plateau in the development of reactant storage and supply systems, and although it was generally felt that the basic technology (supercritical cryogenic storage) would be adequate for the Shuttle, it was also agreed that certain improvements over the Apollo technology would be required to satisfy higher power levels, a different vibration environment, and requirements for increased operational flexibility and safety. High on the list of needed improvements was a better method of loading the reactant tanks because of significant loading problems with the Apollo tanks and the larger fluid quantities to be handled on the Shuttle. Consequently, a clear need was established for greatly improved ground-support equipment (GSE) and operations.

The Apollo 13 incident had led to improved static heater pressurization systems, and much had been learned about low-gravity thermal stratification and its effects in the oxygen tanks on later Apollo flights. Insulation and pressure-vessel mounting improvements had been made as a result of the OTTA and HTTA technology programs, and techniques were available to avoid the compressive, load-bearing insulation scheme of Apollo. A simplified vapor-cooled shield which further increased the thermal efficiency of the hydrogen vessel had been developed. Progress in electronics virtually assured electrical control and protective circuitry for the reactant storage and supply system that was greatly improved compared to the previous electromechanical pressure-switch system.

When the technology and flight programs for the development of fuel cell and cryogenic reactant storage systems in the years preceding the Shuttle are reviewed, it is clear that the availability of the technology is attributable to the failures as well as the successes encountered in these programs, and to the penetrating insight and attention to detail on the part of the technical specialists involved. Although funding was modest in these areas compared to other systems in the Shuttle program, the combination of talented manpower, in-house test capability, and well-planned technology programs was responsible for the "ready" technology state of these systems at the start of the Shuttle development program. A composite summary of these technology and development programs is shown in figure 2.

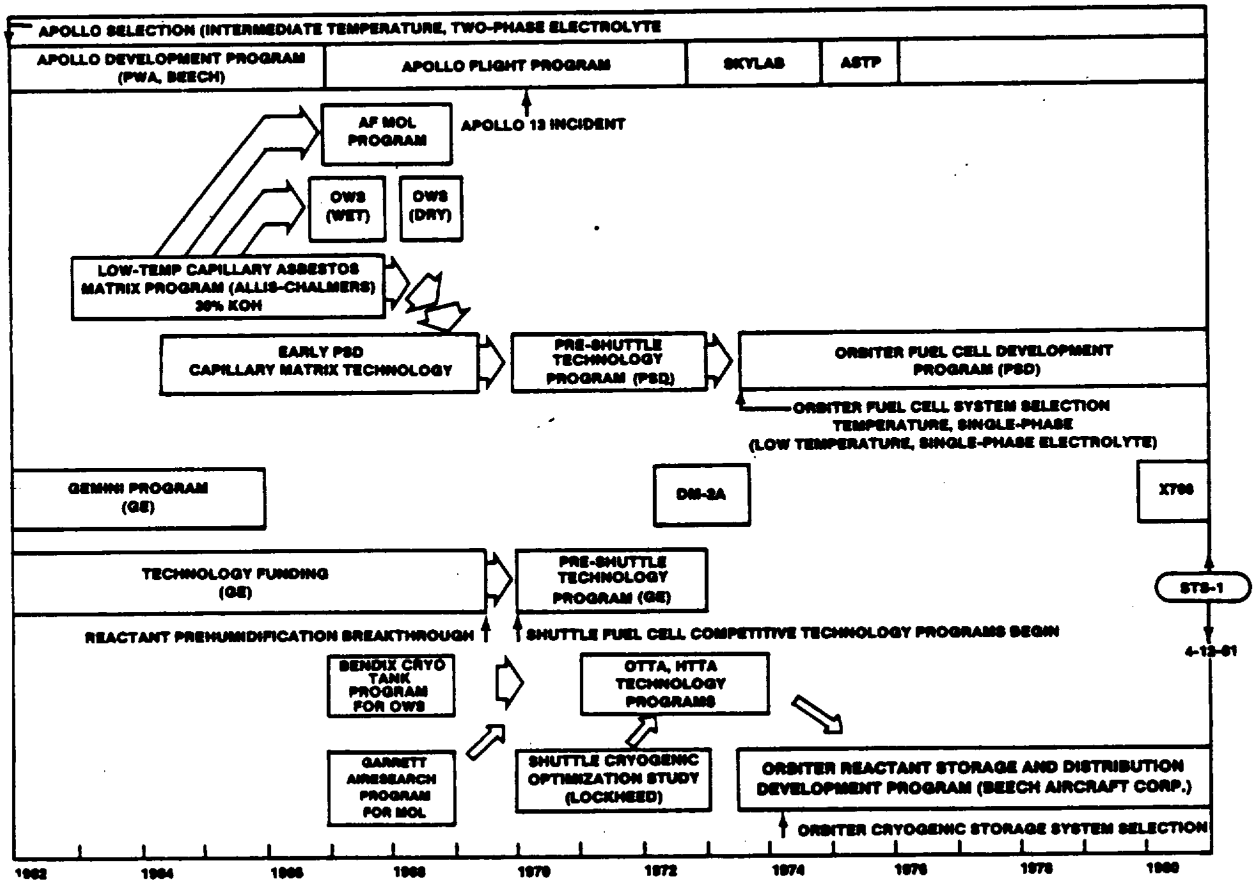


FIGURE 2.- FUEL CELL AND CRYOGENIC REACTANT STORAGE DEVELOPMENT AND TECHNOLOGY PROGRAMS.

THE DEVELOPMENT PROGRAM

TEST AND EVALUATION PROGRAMS

Unlike electrical power system development in the Apollo Program, which was richly endowed with supporting analytical activity, the principal development channel in Shuttle fuel cell and cryogenic system development was its test program. However, because of the increased emphasis on economy in the Shuttle program, the approach taken in the development phase for both the fuel cell and the cryogenic storage system included a minimum test program which would satisfy program requirements. This test program consisted of element and component supplier tests, thermal vacuum tests, vibroacoustics tests, and checkout tests in the Orbiter, with final integrated system checkouts in the horizontal flight test, the flight readiness firings, and the operational flight test program (STS-1 to STS-4).

Very early in the development program, cell test work at the NASA Lewis Research Center resulted in a change from the original platinum-palladium catalyst to the gold catalyst now used in all cells. This change provided increased efficiency and thereby a significant system weight decrease, since two powerplant substacks could then be used instead of the three originally required for each fuel cell powerplant.

Early development fuel cell units of the compact capillary matrix type were the PC8B-1 and the PC8B-4. Tests of the PC8B-1 led to many changes in the proposed Shuttle design, including the innovative dual-feed oxygen system and Noryl end plates. The PC8B-1 test program emphasized the need for alined nubbins and other flow field changes.

Other tests performed at JSC also provided direction for the development program. One example is the investigation of the cold cathode activation procedure, found to be beneficial through early PSD testing, whereby the cells were starved of oxygen after shutdown by supplying an inert gas to the cathode, with hydrogen on the anode, while applying a load to the system. This procedure prevented the 0.5-millivolt per cell unrecoverable voltage losses associated with conventional shutdown procedures and enabled accurate performance predictions, thus reducing the rate of performance degradation of the powerplant. This is one of the reasons the flight powerplants have performed better than originally predicted from the qualification test results.

In addition to the designated qualification powerplants and development units, two developmental powerplants and some component hardware were purchased by JSC for special tests and evaluations to complement the mainstream development program. The DM2A fuel cell was a Shuttle prototype unit consisting of one flight-configured, 32-cell electrical generating stack and a nonflight accessory section. This powerplant was tested at the JSC Thermochemical Test Facility, primarily to provide insight into long-term thermal vacuum environment performance and degradation characteristics early in the Shuttle development program (ref. 20). It successfully ran for 5000 hours at a simulated Shuttle average load of 4.5 kilowatts, with an average loss of less than 1 volt over this time period. In addition to determining degradation characteristics, test engineers mapped the operating characteristics of the powerplant for the full range of Shuttle conditions and evaluated power-up capabilities, transient load responses, purge requirements, and diagnostic techniques. Procedures for starting and stopping the powerplant were also developed and verified in this program.

Another development powerplant, X708, was tested at JSC in 1978 (ref. 21) to evaluate a fully flight-configured Orbiter powerplant over various operating regimes at sea-level pressure and in a thermal vacuum environment. Although there were minor differences, the stack was essentially identical to the present Shuttle fuel cell stack and consisted of two 32-cell, power-producing stacks electrically connected in parallel. The powerplant arrived at JSC having approximately 2000 equivalent hours of operation, and approximately 1000 equivalent hours were added in the course of the tests. Such things as the effects of long periods of open circuit, postlanding cooldown, and short-term high power levels were evaluated. These tests confirmed operation within specification limits for the sea-level and vacuum tests and were extremely useful in thermal mapping of the coolant loop during the cooldown, high power, and open-circuit tests.

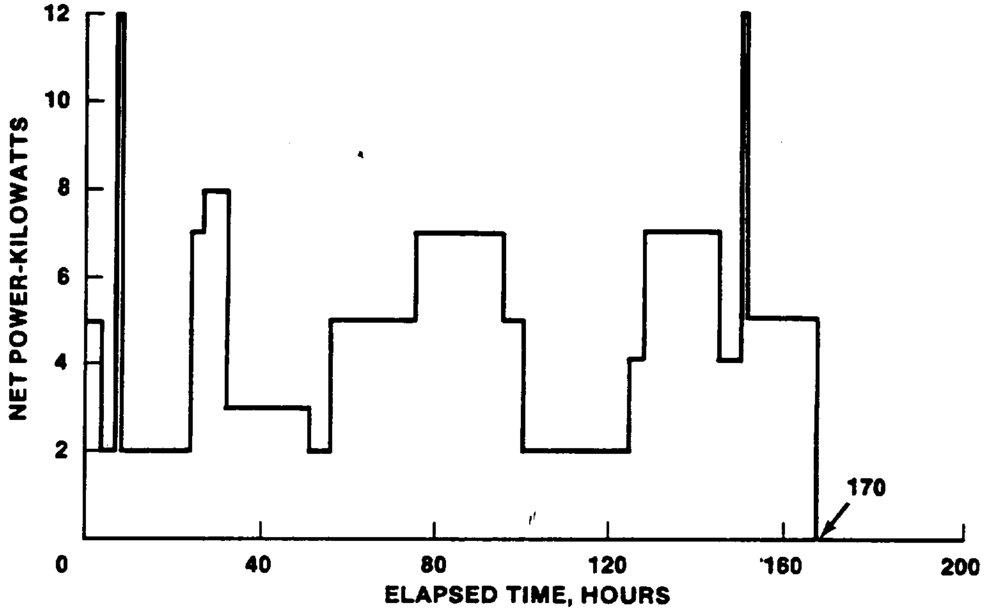
Other fuel cell tests were performed at JSC on its FC-40 fluid breadboard test loop. An example is the investigation performed to develop techniques and procedures for removing dissolved gas from the fuel cell coolant fluid before vacuum filling the coolant system.

Although development problems in the fuel cell program could well be classified as "system level" and "component level," it is perhaps more meaningful in this paper to discuss in some detail the three most important problem areas from the standpoint of meeting and solving the challenges of system development. The first important area was a water removal problem first evidenced in 1975 by hydrogen pump seize-up during vibration testing of a powerplant simulator. A failure investigation revealed impeller interference within the housing, as well as contamination inside the pump. Consequently, the hydrogen pump was redesigned to include a circulating filter, increased clearances, and a larger diameter impeller to maintain existing pumping capacity despite the larger clearances. The redesigned pump-separator unit successfully completed vibration and other tests, and it was not until the next year, when attitude position testing on development powerplant X707 began, that further problems arose. Surge and stall problems occurred in the right-hand launch attitude tests. Investigation revealed that impeller rim purging during startup would eliminate surge and stall during right-hand position starts and operation. This revelation led to the third-generation production pump, which incorporated two purge ports in the impeller rim. Tests on this design revealed that purging did not solve the surge and stall problem in the right-hand position during startup, and out of this series of additional problems arose a fourth-generation, self-aspirated pump. Unfortunately, this design did not eliminate the surge and stall problems. It was also determined during pump testing that condenser backflow was sometimes experienced during certain expected launch acceleration loads (-Z). The fuel cell specification was then changed to incorporate expected launch and landing accelerations, and a condenser backflow investigation was initiated. This investigation resulted, in 1978, in further pump development activity in which 10 design changes were made and, subsequently, in a fifth-generation pump. The condenser backflow investigation also precipitated other changes in the condenser inlet header and the condenser aspirator pickup points. The result of these changes was the designation of "left-hand" and "right-hand" powerplants, according to their position, and resultant orientation, in the vehicle. Aspirator suction tube kits were fabricated for field conversion from the "right-hand" to the "left-hand" configuration. The redesigned condenser and fifth-generation hydrogen pump successfully completed all attitude tests as well as a 2000-hour qualification test. In fabricating the redesigned condenser, it was observed that inadequate deburring before the welding process left metal "burrs" inside the condenser which could have led to serious contamination problems in the flow system had this problem not been corrected by tightening quality control procedures. This quality problem is considered minor in comparison to the other problems associated with the water removal system.

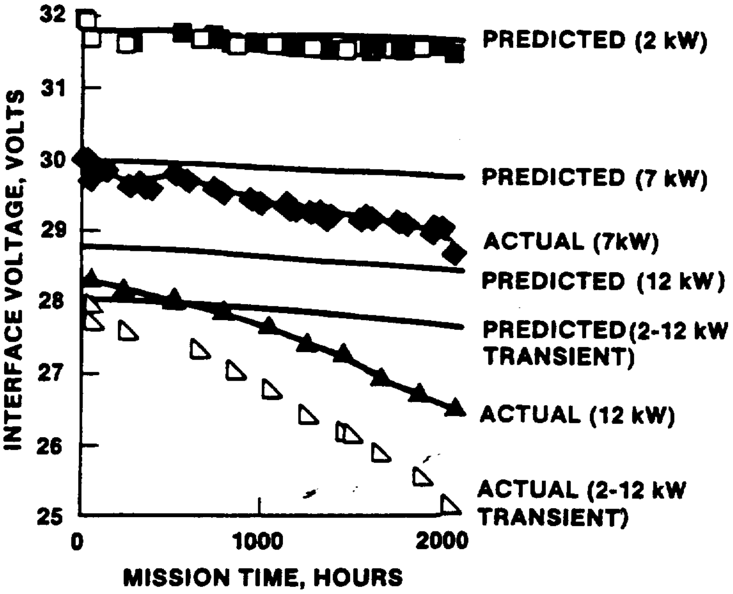
The second important fuel cell development problem occurred in the process of plating the magnesium separator plates which provide the flow channels for the reactant gases and the coolant. Magnesium was chosen for the plates because of its lighter weight, and it was used in the fabrication of the hydrogen and oxygen plates as well as the coolant plates. To isolate the magnesium from water in the stack to prevent corrosion, it was necessary to cover these plates with a thin (1.5 mil) layer of nickel. Then, to preserve electrical conductivity and to provide oxidation protection for the nickel, a layer of gold 0.2 mil in thickness was electroplated onto the nickel coating. The magnesium plates were first dipped in a zincate solution to promote adhesion of an intervening layer of copper, which was required by the industry-standard process to facilitate adhesion of the nickel coating. The problem involved plating defects in the nickel layer, and was ultimately found to be caused by insufficient process control and quality checks. Flow distribution requirements necessitated the use of a complex waffle-pattern plate geometry, which contributed to the formation of tiny blisters on the plate surface. These blisters were the result of a coating system breakdown which exposed the magnesium. The industry-standard process, although well established for other applications, was found to be inadequate for this specific application. To complicate matters, two vendor changes occurred in the manufacture of the finished plates during this time period. An investigation was then conducted which resulted in a better understanding of quality issues and requirements in plate production and in improvement of visual and X-ray standards. After process control was tightened, the improved inspection techniques helped in reducing scrap rates.

The third fuel cell problem of major import involved an abnormally high performance degradation in the qualification unit. The specification requirement for a fuel cell powerplant dictates a voltage regulation between 27.5 volts and 32.5 volts at the fuel cell terminals for loads between 2 kilowatts and 12 kilowatts. This specification applies in either a power-up or a power-down direction, as well as in steady state, over a period of 2000 hours when the average load on the powerplant is 4.5 kilowatts. The qualification power profile is shown in figure 3(a), and these loads were to be repeated for the qualification test until the powerplant had been operated for the required 2000 hours. At approximately 600 hours into the test, the powerplant fell below the 27.5-volt minimum requirement during a 2-kilowatt to 12-kilowatt power-up transient as shown in figure 3(b). This figure also shows performance losses at various steady-state power levels. It was decided at that point to continue the test for the purpose of certifying the powerplant accessory section for the required 2000 hours, and this was accomplished. The powerplant accumulated 2061 hours, with 53 starts, before teardown and analysis began. Meanwhile, because of this problem, production powerplants could only be considered qualified for 600 hours, or the equivalent of about four Shuttle flights. An exhaustive investigation was launched into the manufacturing history and build characteristics of the cell and into multicell rig and powerplant operational differences to find the cause of the premature performance degradation. The historical data search revealed that the performance decay was a function of numerous extensive powerplant load variations, start/stop cycles, and extended operation between cycles. Additionally, the anode (H_2 electrode) was suspected, since its voltage decay was worse than that of the cathode at high power levels. The post-test teardown confirmed this suspicion, since white calcium silicate deposits were found on the anode surface and were judged to be a primary contributor to anode performance degradation. Examination of used, new, and virgin electrolyte matrix material (asbestos) showed significant quantities of calcium (as much as several percent) in the asbestos material. Tests indicated that the calcium deposit transferred to the anode, where it inhibited the hydrophobicity of the anode. Without hydrophobicity, the catalyst reactant sites become excessively wetted by electrolyte, which masks reactant from the catalyst area and causes a decrease in performance. Cathode (O_2 electrode) performance was essentially unchanged from initial conditions, although the occurrence of small (10 mV/cell) positive and negative shifts caused performance changes from one start to the next (cathode activation losses). After the matrix material was found to be the source of the calcium deposits, it was theorized that electrolyte volume changes (i.e., a washing effect of electrolyte back and forth in the electrolyte reservoir plate (ERP) as a result of load changes and start cycles) provided the mechanism for calcium deposition. At this point, a plan of action was initiated to develop methods for calcium removal. Adding cells to the stack and even changing fuel cell vendors were options discussed. Tests on a two-cell stack using new cells to investigate the high initial performance degradation and the effects of startup and shutdown were initiated by JSC.

Approximately 1 year of intensive effort on the part of JSC, its prime contractor, Rockwell International, and the fuel cell manufacturer, the United Technologies Corporation PSD, was required to solve this problem, and the solution came in the form of two processes. The first, an electrode floccing process, consisted of adding a floccing agent to the colloidal dispersion of catalyst agent



(a) QUALIFICATION POWER PROFILE.



(b) QUALIFICATION TEST RESULTS (P760105).

FIGURE 3.- ORBITER FUEL CELL QUALIFICATION PARAMETERS.

used to coat the surface of the electrodes. Use of the floccing agent produced an electrode of more uniform consistency, thereby minimizing cell-to-cell performance variations. The floccing process was already in use in the PSD fuel cell developed for the U.S. Navy and in the NASA Lewis Research Center fuel cells, and it was incorporated as a no-cost improvement in the Orbiter program. The other process, that of leaching the asbestos matrix material to remove calcium impurities, involved reacting the calcium in the matrix with an organic acid and rinsing away the soluble reaction product. Figure 4 is a comparison of original qualification powerplant performance with later performance obtained after incorporation of the floccing and leaching processes. Here, individual cell

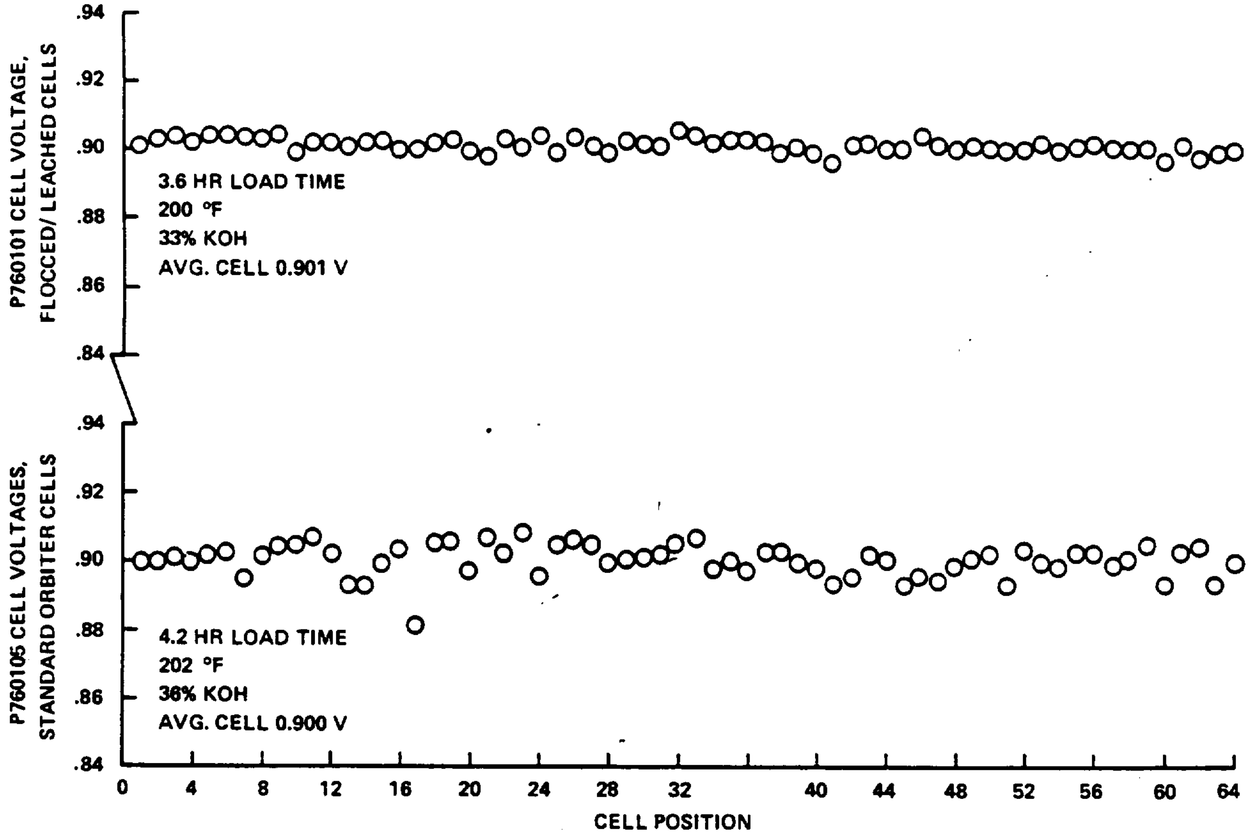


FIGURE 4.- COMPARISON OF STANDARD AND FLOCCED/LEACHED VOLTAGE PROFILES AT 12 kW.

performance is plotted at various loads for both powerplants. Although operating time is insufficient to accurately evaluate these cell process changes, NASA expects powerplant life to reach the 2000-hour goal with the present two-stack configuration. This powerplant is literally being qualified in flight, and all units currently are at or above predicted voltage levels. One powerplant has accumulated approximately 800 hours of flight operation with no noticeable degradation.

A further change later in the development program to a three-stack powerplant configuration was implemented in response to increased power requirements for the Orbiter. This change provides two avenues for additional operational flexibility, namely, longer life (NASA predicts more than 4000 hours) at a design average power level of 4.5 kilowatts or higher load capability (15-kilowatt peak per powerplant) for Shuttle missions. Figure 5 is a comparison of the two- and three-substack configurations for various steady-state powerplant loads.

Other fuel cell development problems, although significant, are considered relatively minor in comparison to the three just described in terms of impact to the program. These less important problems are listed below the major ones in table 1. The problems, the time of occurrence, the causes, and the corrective actions taken are shown.

Cryogenic storage development testing was accomplished for the most part at the Beech Aircraft Corporation, Boulder Division, where two test units, a dynamic model and a thermal test article, were extensively utilized. The dynamic unit was used in the development of the girth ring, the support straps, and the pressure vessel and to solve fill and vent line problems. The thermal test article was important in understanding the thermal-acoustic oscillation phenomenon and in the development of calibration procedures for the capacitance quantity gage inside the tanks. These test units are still in use today and have been used at JSC for relief valve and fill and vent line testing.

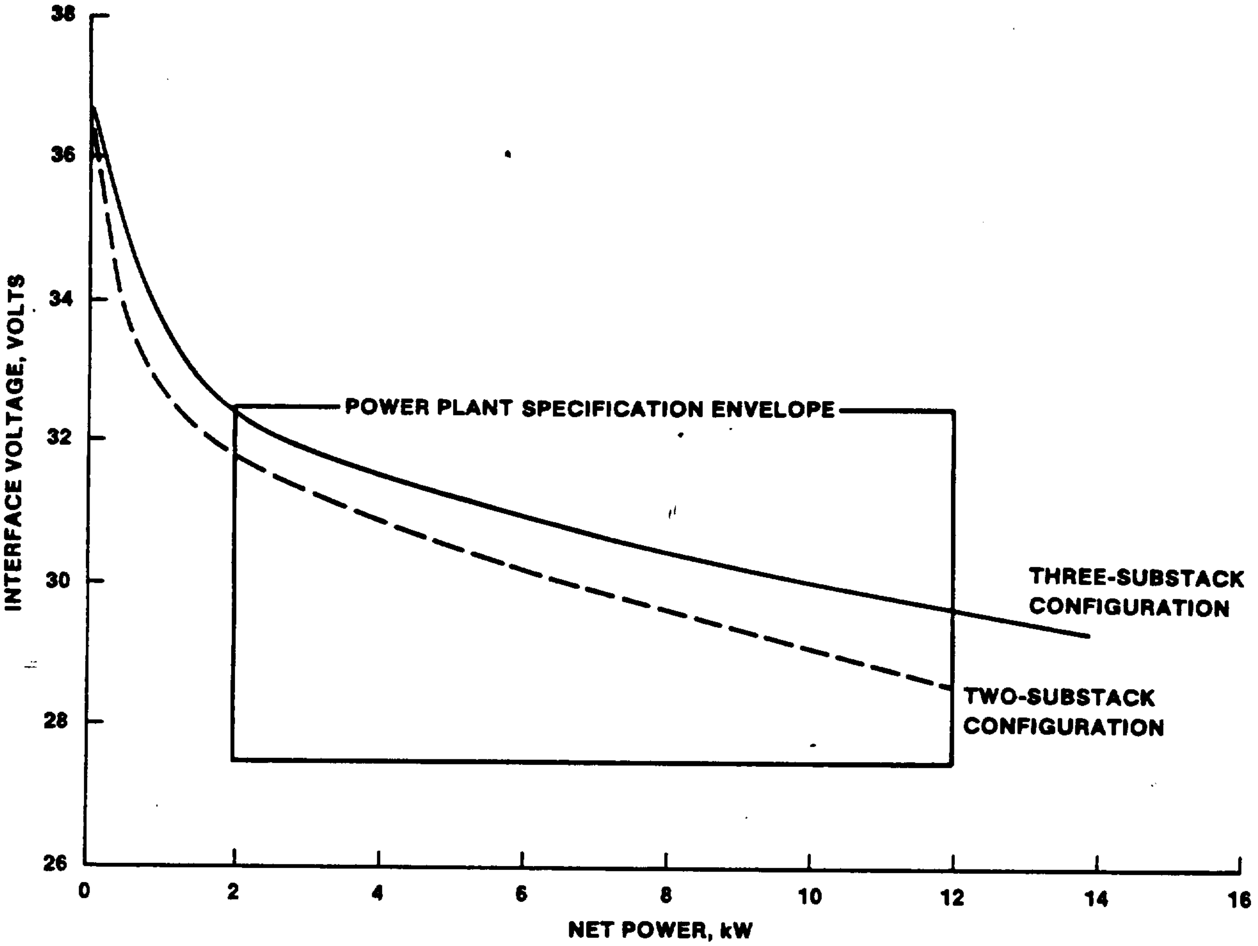


FIGURE 5.- COMPARISON OF PERFORMANCE DATA FOR TWO-SUBSTACK AND THREE-SUBSTACK POWERPLANTS.

Engineering improvements in cryogenics were needed in four areas: tank pressurization, inner vessel suspension, protective electrical circuitry, and GSE. The Apollo 13 incident had led to improved static heater pressurization systems, and although internal and external pressurization methods were being considered for the Shuttle, the general consensus was to maintain the internal scheme used on Apollo but to use no fans in either the Shuttle hydrogen or the Shuttle oxygen tank. Although the static internal pressurization technique had been flight-proven in the redesigned oxygen tanks used on later Apollo and subsequent flights, the reactant flow demands of the Shuttle system were approximately seven times greater than those of Apollo, and the increase caused a sharply higher localized heat influx at the heater probes. For example, the maximum heat input to the single heater probe in the redesigned Apollo oxygen tank was 150 watts. In the Shuttle oxygen tank, maximum heat input is 1000 watts. For this reason, the heater element configuration was changed and two heater probes are used in each tank as opposed to the single Apollo probe. The major unknown factors in the pressurization area at the beginning of the tank development program were the degree of thermal stratification expected in these larger tanks and the effects of stratification on system performance. These unknowns were later quantified and understood in the course of the development and flight test programs.

In remembrance of the problems encountered in the Apollo pressure-vessel suspension system, Shuttle designers used the increased knowledge gained in the OTTA and HTTA technology programs by choosing filament-wound S-glass support straps and using them in a tensile-loaded configuration, as opposed to the Apollo compressive load-bearing insulation scheme. This choice eliminated not only mechanical problems caused by internal vessel rotation but also localized high-heat-leak areas through the compressed insulation. Here again, the technology programs were rewarding in providing an increased level of intelligence for Shuttle development.

TABLE 1.- PROBLEMS ENCOUNTERED IN ORBITER FUEL CELL DEVELOPMENT PROGRAM

Problem	Time frame	Cause	Corrective action
Major			
Water removal system			
H_2 pump stall	1975	Low impeller clearance, contamination in pump	Pump redesign (filter, increased clearance, larger diameter impeller)
Right-hand launch attitude stall	1976-78	Water buildup in pump rim	Impeller rim purge port and aspirator installation, pump current measurements, pump/separator redesign, left-hand/right-hand powerplants (aspirator suction tube kits)
STS-2 fuel cell failure	1981	Pump rim aspirator blocked by small foreign object; caused progressive fuel cell flooding with resultant high pH and voltage loss	Improved contamination control; pump redesign (eliminated pump rim aspirator); material change (parts changed to stainless); stainless steel filters
Nickelplating (Mg plates)	1974-75	Insufficient process control and quality checks	Improved process control in plate production and improved nondestructive evaluation techniques
Performance degradation, qualification powerplant	1979-80	Calcium deposits on anode	Floccing and leaching
Other			
Dynamics (vibration)	1975	Allowable component stress levels exceeded	Support lines added, other fixes implemented to reduce stress levels
Condenser fabrication (burrs)	1982	Lack of quality control in condenser retrofit aspirator	Manufacturing procedures revised to include deburring; condensers reworked
Thermal control valves	1977	Contamination in piston relief slot	Improved cleaning methods
	1982	Thermal expansion, entrapped fluid	Improved manufacturing requirements, groove redesign for 3-substack fuel cell
Water trap	1979	Corrosion in housing - material incompatibility	Material change - Al to Inconel 600
Coolant pump seizure	1980	Coolant fluid expanded with increased temperature forcing can into stator	Stator can perforated to accept coolant volume change
Dual pressure regulator (venting)	1979	Contamination	Quality control improved

The optimization techniques developed in the OTTA and HTTA technology programs led to the selection of double silverized Kapton multilayer insulation with nylon net spacers, although heat leak minimization requirements were not as demanding because of planned higher reactant usage rates. Collectively, these improvements resulted in significantly lower cost, complexity, and weight for the Shuttle reactant storage system.

A third major improvement in the Shuttle tanks compared to the Apollo tanks is in the electrical protective circuitry. Each Shuttle hydrogen/oxygen tank set contains an electrical control box (mounted on avionics cold plates), which contains differential current level detectors, control pressure conditioners (CPC's), remote power controllers (RPC's), control drivers, and the logic required to control the tank heaters and to provide overload protection in case of heater fault.

The fourth item requiring considerable attention in the development program was GSE. In an effort to avoid the difficulties of loading the Apollo tanks, much consideration was given to the GSE early in the program. As a result, larger lines, better insulation, and the absence of tank loading problems were characteristics of the Shuttle program. At JSC and Beech Aircraft, hydraulic pressurization techniques were developed to pressurize the tanks after loading, and procedures were developed at JSC to assure adequate reactant purity at filling. These techniques and procedures resulted in decreased tank loading times.

Although the reactant storage system development program was relatively smooth compared to the fuel cell program, several problems were encountered. These problems can be loosely separated into three categories: dynamics, thermal-acoustic phenomena, and fabrication techniques.

Dynamics (i.e., vibration) problems were of two types. The first - definition of the vibration environment for the system - involved no hardware failures but has been an annoyance from the beginning of the program to the present time. Because of the complex configuration of the interreacting support struts and straps with their multiple degrees of freedom, it has been virtually impossible to perform an adequate dynamic analysis of the system to determine correct vibration levels for dynamic testing. This difficulty has caused many changes in the test requirements, and this issue is still not fully resolved, although the latest tank configuration has been certified for the required 100 missions. The second dynamics problem was related to the first in that it was partly due to a lack of understanding of the vibration environment, but was strictly a components problem. Many components (e.g., tank heaters, capacitance probe, and vac-ion pump) were failing when vibrated to a level believed to be much more severe than that expected in flight. The support straps failed because of fatigue, and the electrical signal-conditioning box almost completely disintegrated during an early development test. The signal-conditioning box was found to be reaching a resonant frequency on the girth ring on which it was mounted, and vibration isolators were required to solve this problem. The fill and vent lines cracked in the hydrogen tank, and this failure led to a complete redesign of these lines in both the hydrogen and oxygen tanks. (The oxygen tank redesign is in work.) Only the pressure vessel, the outer shell, and the tank's girth ring needed no modification after vibration tests. Electrical problems occurred with transistors and diodes failing in the CPC. An embrittlement problem arose in connecting the lead wires to the heater elements; this problem required a manufacturing process change. Thermal-acoustic oscillations discovered early in the program in the hydrogen tank caused pressure change amplitudes of 20 ± 10 psi, which not only produced problems for the pressure control system but also increased tank heat leak by 200 percent. To damp these oscillations, an orifice was put in the fill line and the line was insulated. Extensive JSC in-house testing resulted in both the discovery of this problem and the evaluation of the design fix.

Although extensive spark ignition tests had been performed in the Apollo Program to determine minimum energy levels required for ignition of combustible materials in a high-pressure oxygen environment, later discoveries in the 10 years following the Apollo 13 incident modified these results somewhat. The most significant of these discoveries was that Teflon will ignite in this environment at energy levels lower than originally expected. Extensive testing was performed on the Shuttle signal conditioner to determine whether it was capable of delivering localized energies in the vicinity of the capacitance probe (the only tank component containing Teflon) sufficient to produce ignition. The results were negative and no changes had to be made to the system.

Another Shuttle development problem which constituted a significant challenge concerned the manufacturing process for the pressure vessel. To complete a pressure vessel, its two preformed hemispherical shells are clamped together carefully at many points and, after precision alinement and measurement checks, the hemispheres are welded together. Because no problem was suspected, the measurements originally were not rechecked after the welding process was completed. Later, discovery of pressure-vessel mismatches caused concern for the integrity of the vessel. An additional qualification test was run on a pressure vessel with a known severe mismatch, and, following this test, the vessel was subjected to a burst test which proved that excessive mismatch did not cause burst pressure problems. Tanks currently are being flown with a lower degree of mismatch than that of the burst-test specimen, but two significant corrective actions have been initiated. The first was a procedural modification requiring recheck of the vessels for mismatch after welding is complete. The second corrective action involved the development of an ingenious nondestructive evaluation (NDE) procedure to X-ray for pressure vessel mismatch on existing tanks, viz, completely fabricated tanks with an outer vessel. Considerable cost savings were realized using this procedure, since not all tanks have the mismatch problem.

Table 2 is a summary of major reactant supply system development problems, the time frame in which they occurred, the determined cause, and the corrective actions taken. This table, as with the comparable fuel cell table presented earlier, is not intended as a complete problem list but only to highlight some of the most challenging problems encountered in the program.

Although testing and evaluation is continuing on such issues as certification of empty reactant storage vessels for launch, fuel cell startup heater design issues, and higher-than-anticipated vibration levels in flight, a technological plateau was reached in 1981 when both the fuel cell and cryogenic systems were declared ready for the first orbital flight test. From this plateau, one could look back down the steep slope representing the challenges which had been overcome in bringing these two systems to a state of flight readiness. Many improvements had been made in these systems since the Apollo Program. A comparison of the most significant characteristics of these Shuttle systems with those of Apollo is shown in tables 3 and 4. The pause at this plateau was brief, however, because on April 12, 1981, the launch of STS-1 signaled the beginning of a new era of developmental flight testing in the early Shuttle flights which held still more surprises.

FLIGHT EXPERIENCES

In the first four development flight tests, several problems were encountered in the fuel cell and reactant storage systems. Only one of these problems could be considered major, that being the STS-2 fuel cell failure. This problem was traced to contamination in the water removal system. It

TABLE 2.- PROBLEMS ENCOUNTERED IN SHUTTLE REACTANT SUPPLY SYSTEM DEVELOPMENT PROGRAM

Problem	Time frame	Cause	Corrective action
Environmental			
Inadequate tank/component vibration environment definition	1974-present	Complex configuration; multiple degrees of freedom	Vibration requirements modified by flight test data
Component vibration failures	1974-80	Inadequate component vibration environment definition led to overly severe test conditions	Redesign of some components (e.g., fill/vent lines); retest of others at reduced vibration levels; vibration isolators
Thermal-acoustic oscillations (H_2)	1977-78	Thermal instability	Installed orifice in the fill line and improved insulation on H_2 and O_2 fill and vent lines
Electrical			
Control pressure conditioner	1980-present	Cold solder joints, unpotted filters	Component redesign and improved manufacturing techniques
Reactant valve switch	1977	Excessive voltage drop across contacts	Revised manufacturing procedures
H_2 shutoff valve lead wire short	1977	Wire contact with valve cover during welding	Improved inspection techniques
O_2 shutoff valve short	1976	Sharp bends in wires, insulation failed, causing shorting	Wiring and insulation redesign
Signal conditioner combustion hazard	1979	Potential shorting in capacitance probe	Performed hazard analysis and additional off-limits testing to prove adequacy of design and to define design margins
Manufacturing			
Heater wire embrittlement (H_2 tank)	1982 (STS-4)	High stresses developed during high-temperature annealing and gold braze operations, causing embrittlement	Design changes to eliminate heater stress concentration bends; improved inspection techniques
Pressure vessel mismatch	1980-81	Welding process for hemispheres introduced errors; not rechecked after welding	Improved clamping procedures; began using improved radiographic technique to detect mismatch on existing vessels (those produced before the problem was discovered)
Instrumentation			
H_2 quantity transducer shift	1982 (STS-4)	Unresolved to date	Tank depletion can be tracked by quantity comparison with other tanks and known fuel cell usage
O_2 quantity transducer shift	1982	Suspected shift in calibration; cause unresolved to date	Same as H_2 transducer
H_2 quantity gage off-scale high	1982 (STS-3)	Two simultaneous open-circuit conditions in EMI filter sections of signal conditioner	Revised repair/inspection techniques
O_2 pressure transducer	1976	Transducer instability	Revised acceptance test procedure
Control logic failure in H_2 T-0 valve	1981	H_2 T-0 valve control logic defective	Valve replaced, control logic revised

was found that the hydrogen pump was not operating properly because of contaminant blockage of the pump impeller rim aspirator. The blockage caused water backflow through the pump rim into the hydrogen discharge port and eventually all the way to the power section and flooded several cells. This problem resulted in yet another redesign of the hydrogen pump and the water removal system. Included were material changes, the incorporation of filters in the water removal section of the pump, and the elimination of the hydrogen pump rim aspirator in favor of a passive recirculation system. Also, ground checkout monitoring of pump current was emphasized. No further problems have been experienced with this system. A three-substack fuel cell powerplant has also been produced; this unit has recently completed qualification testing and will be flown for the first time on STS-9. The redesigned hydrogen pump was installed on the three-substack powerplant and qualified along with the powerplant after successful completion of powerplant qualification testing. Other fuel-cell-related flight problems include reactant flowmeter malfunctions and a shift in thermal control set points. Both of these are minor by comparison to the hydrogen pump problem, and design or process changes have remedied both problems.

The reactant storage system has performed well on all flights through STS-7 with few problems, none of which caused a mission compromise. The heater wire embrittlement problem, thought to have been solved earlier, did recur on STS-4, resulting in a powered-down heater mode for entry, but per-

TABLE 3.- COMPARISON OF SALIENT APOLLO AND SHUTTLE FUEL CELL CHARACTERISTICS

Characteristic	Apollo	Shuttle[a]
Net powerplant output, steady state		
Min-max, kW	0.6-1.4	2-12
Average, kW	0.9	7
Voltage, V	27 to 31	27.5 to 32.5
Thermal control	Dedicated radiators	Integrated with vehicle ATCS[b]
In-flight restart capability	No	Yes
Restarts allowed	N/A	50 starts with no maintenance 125 starts with maintenance
Reactant purity required (by volume)	0.99995 O_2 0.99995 H_2	0.99989 O_2 0.99990 H_2
Powerplant life, hr	400	2000 with no maintenance 5000 with maintenance
Powerplant weight, lb	245	202
Powerplant specific weight, lb/kW	270	29
Current density at average load, A/ft^2	90	230
Cost		
Development program, million dollars[c]	61.1	22.6 (through OV102)
Production powerplant, million dollars[c]	1.2	2.2

[a] Two-substack powerplant.

[b] Active thermal control system (Freon loops).

[c] Apollo costs in 1971 dollars; Shuttle costs in 1982 dollars.

formance remained nominal with no mission impact. This problem is under investigation, but because of extensive ground checkout, an extrememly low failure rate, and an adequate amount of redundancy to cover uncertainties, no flight impact has occurred. Only two other component failures have occurred in the flight program (excluding random instrumentation failures): a remote power controller and a hydrogen quantity gage. The RPC problem was traced to an electrical problem and resolved, and the quantity gage signal conditioner was replaced (twice) to preclude recurrence. The tank pressure control system works consistently, with no control band drift from flight to flight. Compared to the Apollo pressure control system, the Shuttle system is very sophisticated. It allows predelivery setting of the pressure control band higher for selected tanks, with all tanks in the "auto" position, to avoid callup requirements to the crew for manual tank management. Occasionally, pressure drops of as much as 100 psi in the oxygen tanks, caused by destratification, have been observed during vehicle maneuvers, but these cause no concern since the tank operates at a pressure near 900 psia and the fuel cell minimum pressure requirement is 100 psia. Other minor problems that have occurred, primarily instrumentation problems, are not mentioned here. Review of flight data for the STS-1 to STS-4 missions revealed tank vibration levels which were higher than expected during ascent. This revelation necessitated certain modifications to the oxygen tank fill line and resulted in a redesign and certification of the tank for the more stringent dynamic environment.

TABLE 4.- COMPARISON OF SALIENT APOLLO AND SHUTTLE REACTANT STORAGE SYSTEM CHARACTERISTICS

Characteristic	Apollo	Shuttle
Tank capacity (100% quantity), lb	29 H_2[a] 330 O_2	92 H_2[b] 781 O_2
Tank heat leak at dQ/dm min, Btu/hr	7 H_2 26 O_2	6.7 H_2 20 O_2
Flow rate at dQ/dm min, lb/hr	0.07 H_2 0.73 O_2	0.07 H_2 0.62 O_2
Insulation	Aluminized Mylar	Silverized Kapton with nylon net
Vapor-cooled shield	O_2 (limited) H_2 (forerunner to Shuttle)	O_2 - not required H_2 - simplified
Structural support	Compressive O_2: load bearing H_2: partly load bearing	Tensile Epoxy-impregnated S-glass support straps
Reusability	None	100 missions
Tank operation control	Pressure switches	Cryogenic control box (electronic)
Heater protection	Fuses Stainless steel sheath (O_2: static)	Differential current level detector Double stainless steel sheath (O_2) High-emissivity coating
Tank weight, lb		
H_2	91	227
O_2	80	215
Cost		
Development program, million dollars[c]	15.1	14.4
Production tank set (two tanks), million dollars[c]	0.8	1.6

[a] Apollo baseline: before Apollo 14 - two tank sets (H_2 and O_2); after Apollo 14 - three tank sets.

[b] Shuttle baseline: two tank sets, but as many as five complete tank sets can be installed below payload bay liner.

[c] Apollo costs in 1971 dollars; Shuttle costs in 1982 dollars.

CONCLUSION

Looking back on the vast amount of activity occurring from the early days of the technology programs to the present time, peaks of accomplishment stand out in meeting the challenges faced in developing the present fuel cell and reactant storage systems. These accomplishments include major advances in electrochemical technology, significant mechanical and electrical improvements, much progress in dynamics and thermal engineering, and major breakthroughs in nondestructive testing and manufacturing techniques. Many of these achievements can be traced directly to the NASA predevelopment technology programs.

Collectively, the decisions and efforts of a large number of design and development experts, test engineers, project personnel, and subsystem managers, under the direction of the Orbiter Project Manager, have successfully guided the development of these two Shuttle systems through many problems.

This success was the result of a dedicated team effort by all involved, both NASA and contractor personnel. All should be proud that the challenge has been met and major difficulties overcome to produce the systems which are flying in the Shuttle Orbiter today.

In summary, no failures have occurred in flight which have compromised either crew safety or mission success, although the STS-2 fuel cell failure did cause this mission to be shortened to preplanned minimum mission guidelines; however, more than 90 percent of all high-priority flight tests were accomplished (ref. 22). The STS-2 mission incident also demonstrated important "designed-in" operational capabilities in the presence of a significant subsystem failure. From this standpoint, it can be concluded that these systems have performed well. Development problems still exist, however, which are being diligently worked on at the present time (examples are cryogenic tank heater wire embrittlement and fuel cell startup heater failures in ground test). Because of this continuing effort, future flights should be even safer and better from an operational standpoint. As in any high technology area, further improvements may be required and problems as yet unforeseen may arise in the future, and we must remain prepared to face these new challenges.

VITA

William E. Simon is Deputy Chief of the Power Generation Branch of the JSC Propulsion and Power Division. After joining JSC in 1963, he was involved in the development of the Apollo fuel cell and performed a computerized transient thermodynamic analysis of this system. He served as the Division's senior thermal control coordinator for Propulsion and Power Division Shuttle subsystems from 1972 to 1975. He performed the thermal dynamic power system technology trade-off studies in 1976 for the JSC in-house Solar Power Satellite Study. From 1977 to 1980, he was involved in the development and verification of the Shuttle Integrated Main Propulsion System (MPS). Dr. Simon assumed his present duties in November 1980 which involved responsibility for the Shuttle's onboard fuel cell and cryogenic subsystems, as well as the JSC Government furnished equipment battery program, and advanced electrical power system development for Space Station application.

ACKNOWLEDGMENT

The author gratefully acknowledges the suggestions, insights, and data provided by former JSC subsystem managers Robert R. Rice, Shelby L. Owens, James R. Briley, Fulton M. Plauché, and present subsystem manager Thomas L. Davies. Appreciation is also extended to Rockwell International Project Manager James F. Williams as well as to William E. Romanoski and Henry J. DeRonck, system engineers with United Technologies Corporation, Power Systems Division. Gratitude is expressed to Richard B. Ferguson, former Deputy Chief of the JSC Propulsion and Power Division for valuable insight into the JSC early technology programs. Thanks also go to Mrs. Lynn S. Murgia for her review and comments on the mechanisms theorized for performance degradation within the fuel cell. Recognition is given to the JSC Thermochemical Test Branch, specifically to power systems test engineers David R. Saucier and Norman C. Luksa and to Branch Chief Chester A. Vaughan, for review of the paper and for vital information on the JSC in-house test programs. The author also acknowledges the informative discussions and information on system and component problem histories provided by Marvin F. LeBlanc, quality engineer with the Boeing Company. Finally, thanks go to Mr. William A. Chandler, Chief of the JSC Power Generation Branch, for his review and comments.

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