Molten Carbonate Fuel Cell System Verification and Scale-up

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Research Project 1273-1

Interim Report, January 1981

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NOTICE

Prepared by
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ABSTRACT

The primary goal of this three year Project is to demonstrate the operability of a molten carbonate cell stack, an advanced fuel processor and critical system components in a subscale power plant context. The Project activities comprise three technical tasks: (1) Testing a nominal 2-kW stack of the configuration resulting from other EPRI sponsored work (RP114-2), (2) Testing a nominal 2-kW stack design at elevated pressures, drawing from the process development and design activities being carried out in complementary Niagara Mohawk Power Company and U. S. Department of Energy Projects, and from the cell technology activity in Project RP1085-4, and (3) Testing a pressurized 20-kW "breadboard" power plant comprising advanced fuel processing (adiabatic reformer and gas clean-up systems resulting from Project RP1041-4), a stack of more than 100-cells and critical system ancillaries necessary for operation of dispersed generator power plants. The breadboard power plant will operate on distillate liquid fuels from petroleum and coal. This interim report describes the activities performed in Tasks 1 and 2 during the initial 16 months of the contract.

In the early stages of the contract, a stack that had been tested in RP114-2 was used to evaluate new manifold seal configurations, carbonate vapor scrubber materials, and an approach to rebuilding molten carbonate fuel cell stacks. Single cell tests were used to explore design issues associated with a fixed height mechanical loading system and manufacturing alternatives for a simpler separator plate. Following these tasks, a 20-cell stack incorporating a number of new features was designed, fabricated and tested at ambient pressure. Cell stack features tested for the first time included external manifolding of both fuel and air, a fixed height mechanical loading system and a simpler separator plate configuration. The test verified that:

- Operating performance of the stack was within the range of subscale cells of the same design.
- The stack containment vessel and associated penetrator fittings were acceptable for pressurized operation.

- Stack reactant gas sealing was within design limits.
- Performance of the simplified cell separator plate configuration was acceptable.

The ambient pressure test of this 20-cell stack was suspended after a total operating time of 890 hours and two thermal cycles to prepare the stack and test stand for operation at elevated pressures.

An analysis of the breadboard system to establish test stand requirements was completed. The pressurized stack test stand design was completed and construction has begun. A fibrous alumina/silica material was selected for scrubbing carbonate vapors from the cell stack product streams; this material is being tested on the 20-cell stack.

At this time, the effort is ahead of schedule in terms of stack operation at pressure and in testing system ancillaries. The effort is behind schedule in terms of demonstrating initial cell stack performance consistent with power plant goals.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This interim report describes the first 16 months of activities of a planned 3½-year project that will culminate in the operation of a "breadboard" molten carbonate fuel cell power plant. The breadboard will consist of a 20-kW stack containing more than 100 cells, a fuel processor that will convert petroleum- and coal-derived distillate fuels to synthesis gas for use in the stack, and other critical components needed for the system to function properly.

This project addresses power plant system issues. The breadboard is intended to demonstrate that the power plant system configuration and system interface parameters are understood and that there are no unknown barriers to the development of full-scale power plants. A complementary group of projects, totaling approximately $10 million/year and sponsored by EPRI (RP114 and RP1085), Niagara Mohawk, and the Department of Energy, are underway at United Technologies Corp., General Electric, Energy Research Corp., and Institute of Gas Technology (IGT). These projects are aimed at developing full-scale, low-cost, durable molten carbonate fuel cell stack components. The combined objectives of the multiparty effort are to verify that the molten carbonate fuel cell is ready for engineering development of full-scale power plants beginning in the 1982-to-1983 time frame.

PROJECT OBJECTIVES

The overall EPRI project objective is to demonstrate operation of a subscale "breadboard" power plant at conditions that accurately simulate utility power plant operation. The interim goals, with the progress made toward meeting them described herein, were to design and verify a stack configuration capable of being operated at pressure and incorporating provisions necessary to interface with the thermal-, reactant-, and electrolyte-management systems required in a power plant.

PROJECT RESULTS

The project is ahead of schedule in developing a molten carbonate fuel cell stack suitable for operation in a power plant context. Tests have verified the

suitability of the stack design from the standpoint of reactant distribution and containment, thermal management, electrolyte management, and thermal cycling capability at pressures envisioned for utility power plant operation. As this project focuses on these systems-related issues, the results are gratifying. However, two areas remain a concern: stack performance and durability do not yet meet power plant requirements, and the "fixed height" stack loading system which simplifies reactant containment has not been verified. These concerns are being addressed in the parallel cell technology development projects.

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ACKNOWLEDGMENTS

The effort reported herein was carried out by a number of personnel at United Technologies. The project's technical activities were managed by Carl A. Reiser, and Joseph M. King served as United's Program Manager.

Authors contributing to this volume include Richard F. Buswell, Richard H. Goldstein, Murray Katz, George A. Louis, Donald L. Maricle, Craig R. Schroll, and Donald F. Szydlowski.

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SUMMARY

Development of the molten carbonate fuel cell, under RP114 and other programs, has shown the basic feasibility of the technology and defined the requirements for the commercial design of fuel cell stacks and systems needed for dispersed-generation and central station power plants. This report describes results of the Molten Carbonate Fuel Cell Verification and Scaleup Program being carried out under Electric Power Research Institute Project RP1273-1 from November 1978 through February 1980. The objective of this three year effort is to verify that the molten carbonate fuel cell is ready for engineering development and scaleup by demonstrating the operability of a fuel cell stack with an advanced fuel processor and critical ancillary system components in a subscale "breadboard" power plant. Development of the cell stack repeating elements is being continued in parallel molten carbonate programs.

Activities to achieve the above objectives are carried out in the three technical tasks identified in Table S-1. This report covers the period of activities carried out through conclusion of the ambient presure test of the 20-cell stack evaluated in Task 1, and describes the work initiated in Task 2. No work was scheduled or performed in Task 3 during this period.

Table S-1
TASKS OF PROJECT RP1273-1

TASK 1 -	Design, test and verify a nominal 2-kW stack of the configuration resulting from the complementary Project RP114-2.
TASK 2 -	Design, test and verify a nominal 2-kW stack for operation at elevated pressures.
TASK 3 -	Design, test and verify a nominal 20-kW system comprising a pressurized adiabatic reformer and cleanup system of the design resulting from Project RP1041-4, a pressurized stack of more than 100-cells, and other critical system components in a "breadboard" system mode.

The primary objectives of Task 1 have been met through the assembly and ambient pressure testing of a 20-cell stack which demonstrated that:

- The integrity of cell stack components was satisfactory through 890 hours of testing and one thermal cycle.
- Reactant gas and thermal management were achieved throughout the test.
- The stack and pressure vessel design performed as required for pressurized operation.
- Initial performance of the stack was as expected using reactant gases which simulated power plant operation.

This stack will be tested at elevated pressures when the stack test facility being constructed in Task 2 is complete.

Earlier conceptual design studies, conducted by United in parallel with Project RP114-2, established the requirements for a cost effective full-size stack. The Task 1 stack design used several features of that conceptual design whose development had progressed sufficiently for stack testing. The principal design features of the 20-cell stack included:

- External reactant gas manifolding.
- Fixed-height compressive loading system.
- Simpler (and lower cost) separator plate.
- Electrolyte tile with capability for thermal cycling.
- Containment vessel using inert gas purge.
- Electrolyte vapor scrubbing of vent gases.

The designs of components to demonstrate these features were based on detailed studies of: cell-to-cell reactant flow distribution, manifold sealing materials and configurations, compressive loading system trade-offs, heat transfer for thermal management, electrolyte management requirements, pressure vessel penetrator requirements; and on analysis and studies of the physical properties and structural characteristics required of the individual cell components to establish manufacturing specifications and allowable manufacturing tolerances.

Process development activities in Task 1 verified reproducible manufacturing processes for fabricating one-square-foot size cell components of the foregoing design. The repeat cell components for the 20-cell stack were then fabricated

using these processes, and the fabrication yield rates for components meeting design specifications were:

- Electrolyte tile 82%
- Anode 90%
- Cathode 60%
- Separator Plate 73%

Although these rates are encouraging for a small-scale development activity, improving yields through the development of alternative fabrication processes and component configurations is an objective of parallel Niagara Mohawk and U.S. Department of Energy projects. The stack design and component manufacturing processes to be used in Tasks 2 and 3 can be expected to benefit from these complementary projects.

Figure S-1 shows the Task 1 20-cell stack during assembly. The test program for this stack included:

- Characterization of performance parameters at various conditions of operating temperature and reactant gas utilization.
- Characterization of reactant gas containment as a function of gas cross pressure differential.
- Characterization of the above parameters following a thermal cycle.

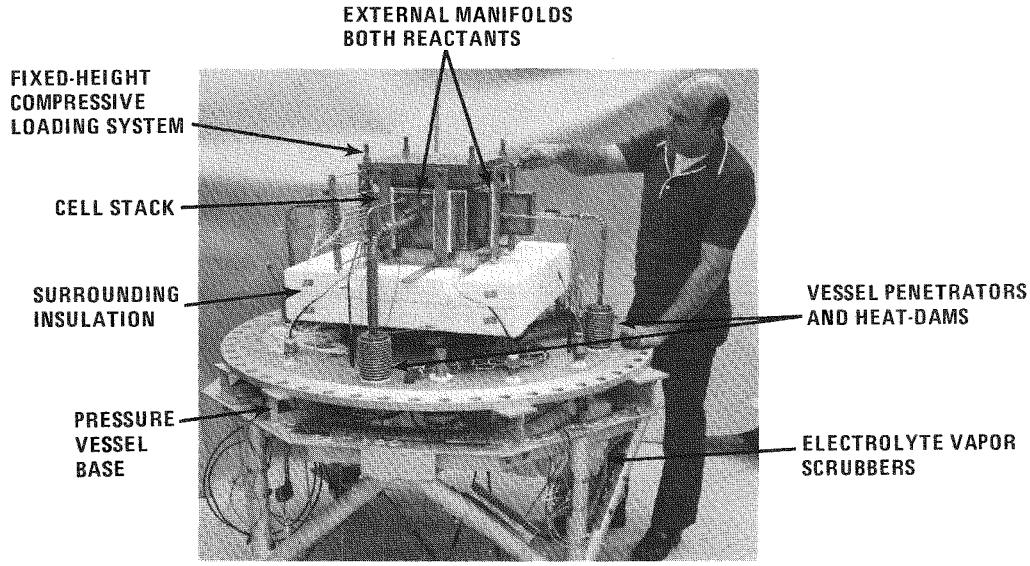

Figure S-1. 20-Cell Stack Assembly

A comparison of the stack test results with the test objectives showed that:

1. Initial performance at the 160 amps/square foot (ASF) rated power point compared favorably to the level demonstrated by bench-scale control cells. This performance comparison is shown in Figure S-2.

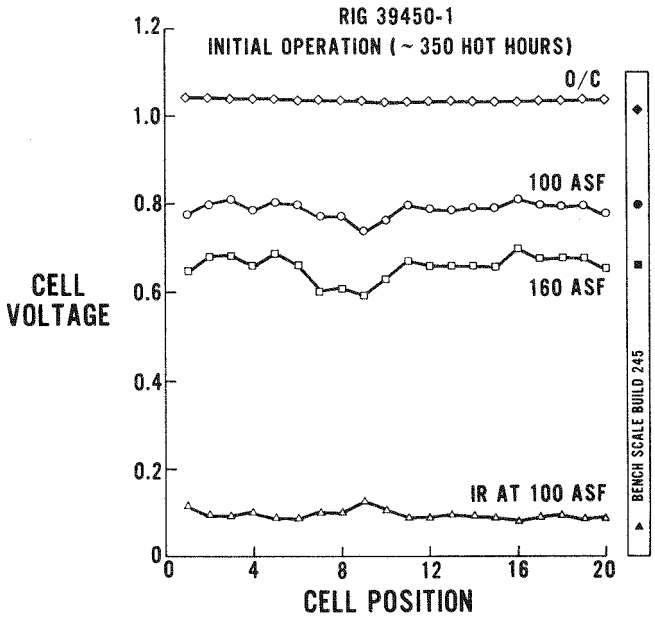

Figure S-2. 20-Cell Stack Performance Comparison (Operating Conditions Provided in Table 2-3)

2. Average performance at 160 ASF was 0.66 volts/cell compared to a pre-test prediction of 0.71 volts/cell. This lower performance was due mainly to higher than predicted cell ohmic losses. This deficiency is believed due to the relatively imprecise location of the cathode support screens used in these cells.

3. No cells exhibited excessive fuel or oxidant utilization sensitivity, indicating that reactant gas distribution from cell to cell was acceptable.

4. Reactant gas containment within cell reactant passages was within the design requirement, demonstrating an overall stack wet-seal efficiency of 99.8 percent of the design rate of fuel flow for a fuel to oxidant pressure differential of 5-inches-of-water-column. This value remained unchanged after the thermal cycle to the conclusion of testing. Figure S-3 compares this favorable test result to the design requirement.

5. Figure S-4 shows that manifold seal leakage was within the acceptable design limit until the stack was shutdown to demonstrate thermal cycleability. During shutdown, the manifold seals were modified to include dielectric barriers to reduce ionic shunt currents between cells in the stack. The change corrected the shunt current deficie

ncies, but resulted in increased manifold leakage. A design which simultaneously satisfies manifold sealing and shunt current prevention is now being pursued.

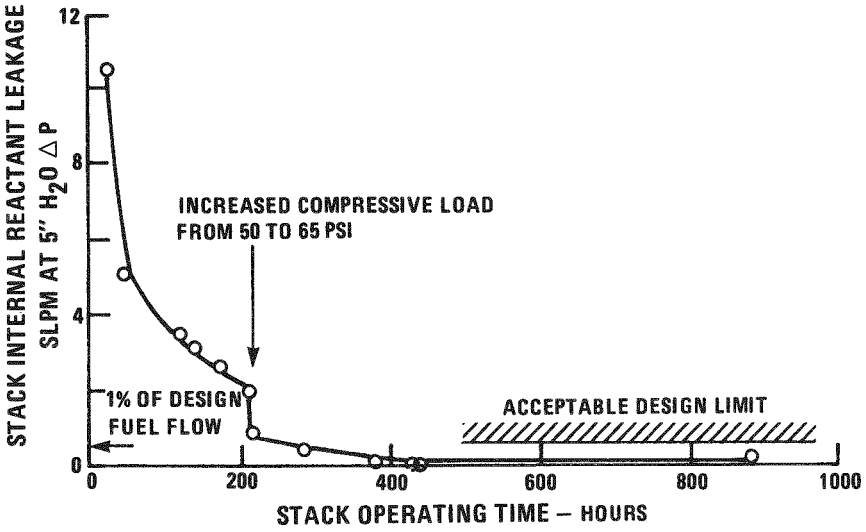

Figure S-3. 20-Cell Stack Internal Sealing Comparison

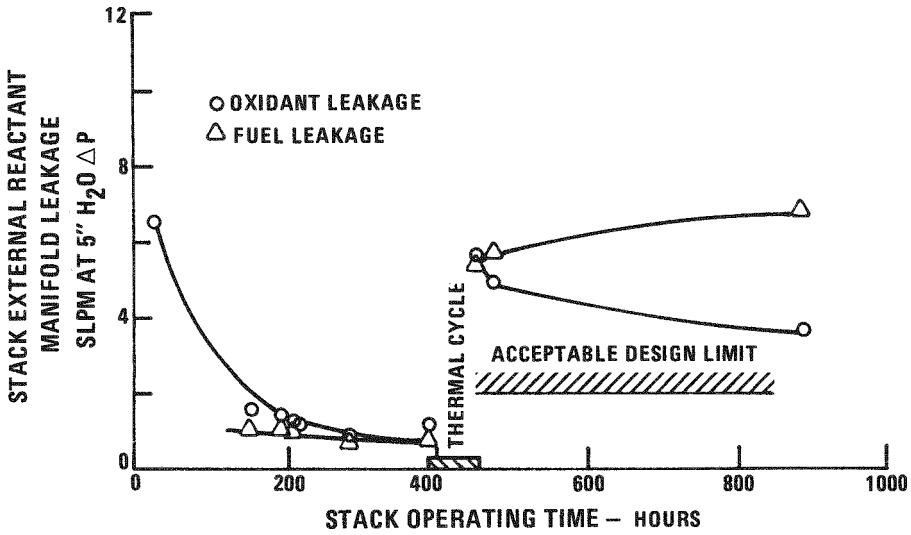

Figure S-4. 20-Cell Stack External Sealing Comparison

At the time the stack was thermal cycled, an attempt was made to transfer the compressive load from the external "followup" system to the internal "fixed-height" system. Stack restart was marked by a performance loss which corresponded to the measured increase in cell internal resistance values. It was determined that the stack compressive load was not transferred to the fixed height system with the procedure used and the load, therefore, was reapplied to the stack through the external system. This resulted in a 75-percent recovery of the performance loss (average net loss was 15 mV-per-cell, per 100 ASF of current density). The load transfer procedure has since been corrected, and the compressive load will be applied to the stack through the fixed-height-system when testing is continued at pressure.

An early effort in Task 1 involved replacement of six poor performing cells from a stack tested in RP114 using three new cells. The rebuild was partially successful in that good reactant sealing was achieved in the rebuild. However, oxide films from the initial test resulted in high cell resistance for the new cells and performance was disappointing. A rebuild procedure including removal of the oxide films will be used for any future rebuild trials. This stack rebuild test also provided the opportunity for initial evaluation of carbonate vapor scrubber materials. Based on the results obtained, a candidate material was selected for evaluation of the scrubber design with the 20-cell stack test which followed.

The scrubber design approach uses a chemically active mat of fibrous alumina/silica to scavenge the electrolyte vapors from the anode and cathode exhaust streams. The scrubbers are configured in an annular design and are sized to remove all of the carbonate vapors expected from 2000 hours of 20-cell stack operation. The ambient-pressure test just concluded showed that the temperature control and pressure drop characteristics of the scrubbers met design expectations, and testing will continue during the pressurized portion of the stack test. Analysis to determine scrubber capacity will be conducted following that test.

An initial study of the breadboard power plant system was performed to establish test stand requirements. Based on this study, the design of the high-pressure test stand and pressure vessel for stack testing were completed and construction is now in progress. The stand and vessel are designed for stack sizes up to 20-kW and for reactant pressures up to 10 atmospheres (150 psia).

Section 1

INTRODUCTION

CELL AND SYSTEM DESCRIPTION

The molten carbonate fuel cell operates at temperatures greater than 1150°F; it provides high fuel to electricity conversion efficiencies and high quality reject heat that can be used to generate additional power or for industrial process heat in a cell stack which doesn't require the use of noble-metal catalyst. References 1 through 9 describe molten carbonate fuel cell power plants and the results of other efforts to develop this technology.

PROGRAM OBJECTIVES AND SCOPE

The technical goal of Project RP1273-1 is to demonstrate the operability of a molten carbonate cell stack, an advanced fuel processor, and critical system components in a subscale power plant context. The program to meet this goal will demonstrate that:

- The system configuration contemplated for a full-scale dispersed generator power plant is understood.
- The design system for advanced fuel cell power plants properly predicts system performance.
- System issues, as yet unknown, present no barriers to the development of full-scale power plants.
- Cell stacks in excess of 100 cells operate properly on the products of an advanced reformer and clean-up system fueled with Number 2 fuel oil or coal derived fuels.
- The electrolyte in large stacks can be managed satisfactorily.
- Critical system issues such as fuel gas carbon formation, anode gas kinetics, anode vent combustion, and scrubbing of carbonates from stack exhaust streams are understood.
- Specifications for critical system components such as heat exchangers and water treatment are understood.

The effort will culminate in testing a "breadboard" power plant system with a nominal rating of 20-kW dc.

RP1273 TASK DESCRIPTION

The effort is carried out in the three technical tasks described below. The program schedule is shown in Figure 1-1.

Task 1 - Stack Test of Configuration From RP114-2

In Task 1 a 20-cell stack will be fabricated and tested, based on the best cell configuration identified in RP114-2 and applicable fabrication techniques identified in the Niagara Mohawk program, to show: that the integrity of cell stack components is satisfactory, that electrolyte, reactant and thermal management are achieved, and that performance is as expected using the range of reactant gases defined in power plant design studies. Carbonate vapor scrubbers and a preliminary anode exhaust burner design will also be tested. This task involves the following activities:

- Developing cell fabrication processes and configurations necessary to achieve reproducible results in one-square-foot cells. The configurations and processes are initially verified in the testing of subscale cells.
- Designing a 20-cell stack of one-square-foot cells.
- Estimating the performance to be expected from the test of the stack under conceptual power plant design conditions.
- Fabricating a 20-cell stack of one-square-foot cells.
- Testing the stack at ambient pressure to demonstrate performance as a function of reactant gas composition, thermal cycling capability, thermal and reactant management, and endurance and operating tolerance.
- Operating the stack at pressures up to 65 psia to determine the impact of pressure on performance and operability.
- Conducting tests to obtain design data on carbonate vapor scrubbers including scrubbing carbonate vapors from the stack exhaust streams.
- Conducting preliminary tests of the anode exhaust burner using the cell stack anode vent gas.
- Determining the condition of stack components after the test and comparing the results of the test with objectives.
- Rebuilding and testing a stack from RP114-2 to define issues associated with stack rebuild.

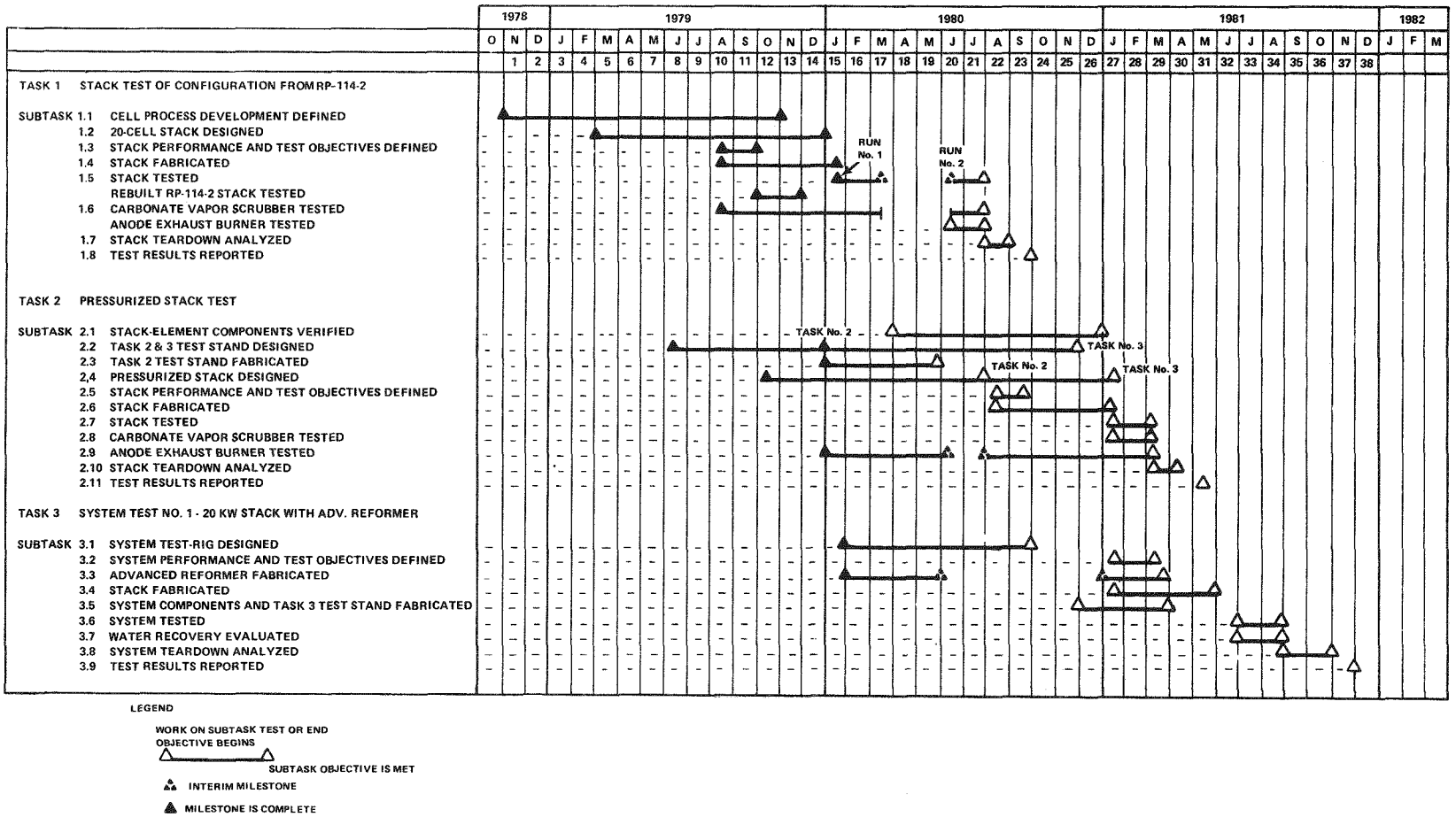

Figure 1-1. Program Schedule for Project RP1273-1

Task 2 - Pressurized Stack Test

A pressurized stack of 20 or more one square foot cells will be fabricated, and tested for at least 1000 hours to show that the stack is compatible with operation at pressure, that the pressurized design is satisfactory, and that the stack will withstand cross pressures imposed by steady-state and transient system operation. A carbonate vapor scrubber and anode exhaust burner will also be tested. This task includes:

- Conducting component tests to verify the suitability of cell stack elements such as seals, manifolds, encapsulation, etc.
- Designing and constructing a pressurized stack test stand.
- Designing a cell stack and its associated pressure vessel.
- Estimating the performance to be expected from test of the pressurized stack.
- Fabricating the stack and pressure vessel based on cell configurations from the results of Task 1, and any improvements demonstrated in parallel programs.
- Testing the stack to a maximum pressure of 150 psia. Tests will be conducted to demonstrate performance as a function of reactant gas composition, pressure, and thermal cycling capability, and to demonstrate thermal management, reactant management, the ability to withstand system induced cross pressure, and endurance.
- Testing an approach for scrubbing carbonate vapor from the stack exhaust streams.
- Testing an anode exhaust burner using the cell stack anode vent gas.
- Determining the condition of stack components after the test and comparing the results of the test with objectives.

Task 3 - System Test of a Cell Stack with Advanced Reformer

Task 3 involves testing a "breadboard" power plant system with a nominal 20-kW rating. The system design will be based on a dispersed generator using distillate liquid fuels from coal or petroleum. The pressurized system will include an advanced fuel processor, a stack of more than 100 molten carbonate cells and critical ancillary components.

An adiabatic reformer will be used in the system to represent advanced fuel processors capable of operation on distillate fuels from coal or oil. The adiabatic reformer (being developed in RP1041-4) converts fuels with end points up to 650°F and sulfur content up to 3000 ppm by weight to a hydrogen-rich stream. The endothermic heat required by the reform reaction is provided by burning of a portion of the fuel plus vent hydrogen from the fuel cell anode in the reform catalyst bed. By providing reaction heat within the bed, the need for heat transfer through the catalyst vessel walls is eliminated and the temperatures required for good catalyst activity in the presence of sulfur can be achieved without requiring higher temperature materials. Sulfur in the incoming fuel is converted to hydrogen sulfide in the reform reactor. In commercial power plants, the sulfur will be removed from the fuel gas stream using a regenerable process. In the breadboard system, the sulfur will be removed in a zinc oxide bed.

The cell stack of the breadboard system will consist of over 100 cells. The exhaust from the anode will pass through a carbonate vapor scrubber and then to a catalytic burner. The catalytic burner will consume the residual hydrogen, and the product stream from the burner (which contains water vapor and carbon dioxide) will be mixed with air to provide the cathode reactant stream. Cell stack reject heat will be removed by recycling the cathode reactant stream. Testing of the breadboard system for approximately 1000 hours will demonstrate: (1) the basic system concept for molten carbonate fuel cell dispersed generators operates properly, (2) the interfaces between system components are properly understood, (3) the fuel cell stack and critical ancillary components operate properly in a power plant system environment. Testing in a realistic power plant environment will also identify any unknown system issues. Because the system test will require a large number of cells, it will provide initial demonstration that cells can be manufactured reproducibly and that design issues associated with stacking and operating a large number of cells are understood.

Task 3 involves the following activities:

- Designing the system test rig to represent basic elements of a dispersed molten carbonate fuel cell power plant. Manual control of the rig will be assumed. The system test rig will include an adiabatic reformer and clean-up system, a cell stack, carbonate vapor scrubbers and an anode exhaust burner.

- Estimating the performance to be expected in system testing.

- Fabricating and testing an adiabatic reformer and clean-up system capable of producing sufficient fuel gas for the stack. The reformer will be based on a design from RP1041-4. A fuel vaporizer will also be designed and tested prior to fabrication of the adiabatic reformer.

- Fabricating a 20-kW stack and pressure vessel based on results of Task 2 and concepts demonstrated in other programs.

- Testing the system test rig to show that (1) the system design for dispersed molten carbonate fuel cells operates properly, (2) that the interfaces between system components are understood and (3) that all system components operate properly. Initial system operation will be on Number 2 fuel oil. Subsequent operation will be on a synthetic coal liquid.

- Determining requirements for system components based on results of the test.

- Determining the condition of system components after the test and comparing results of the test with objectives.

REPORT STRUCTURE AND TIME PERIOD

The RP1273-1 effort began in November 1978. This report covers the 16 month period from the beginning of that effort through efforts associated with design and test of the Task 1 stack at ambient pressure which was concluded in March 1980.

Section 2

TASK 1 STACK TEST OF CONFIGURATION FROM RP114-2

OBJECTIVES AND SCHEDULE

The Task 1 activity during this report period is shown in Figure 1-1. All subtasks have been completed through the ambient-pressure test phase of the Task 1 20-cell stack (Run No. 1). Elements of Task 1 remaining to be completed are: test of the 20-cell stack at elevated pressures in Subtask 1.5, continued testing of the carbonate vapor scrubbers and initial testing of the anode exhaust burner at elevated pressures in Subtask 1.6, stack teardown and analysis in Subtask 1.7, and reporting final stack test results in Subtask 1.8. A discussion by subtask follows.

SUBTASK 1.1 - PROCESS DEVELOPMENT

The objective of this subtask was to develop manufacturing processes required to produce the repeat parts for the Task 1 20-cell stack test. Since the purpose of this test was to evaluate the configuration developed in RP114-2, the approach required developing reproducible manufacturing processes to fabricate one-square-foot size cell components of this configuration.

Process development of the electrolyte tile was obviated following a decision to use conventional compression molded tiles, virtually identical to those used in the previous stack tested in RP114-2. At the time this decision was made, electrolyte tiles made from the Niagara Mohawk sponsored low-cost fabrication technique had not been proven sufficiently and compression molded tiles using low-cost materials from the RP114-2 program had not shown sufficient thermal cycle capability. Since the compression molded tile is not considered a candidate electrolyte retaining structure for a commercial power plant, no significant investment was made in process development for this component.

Electrodes used in previous molten carbonate stacks were vendor supplied. A program decision was made to develop a capability at United to produce these parts in

order to improve program turnaround time. Thus, processes were developed for pilot production of anodes and cathodes. The electrode fabrication work involved sintering powdered nickel to form components with controlled pore spectra that met the design dimensions.

The stack design using external manifolds for both fuel and oxidant distribution required developing a new separator plate. Fabrication trials investigated electron beam and laser welding technology for joining the parts, aluminizing for corrosion protection in the seal areas, and a final heat treatment for flattening and stress-relieving the parts.

Electrolyte Tile Fabrication

Twenty-three of the twenty-eight conventional electrolyte tiles molded met the 20-cell stack design requirements. Densities were 97.55 ±0.85-percent of theoretical density, and were within design specification. Average thickness variation within each part was 0.0031 inches. Based on data from the last 20-cell stack tested in RP114-2, this improved thickness control should have provided improved cell performance. Process control data for each tile used in the 20-cell stack is shown in Table 2-1.

Table 2-1

DENSITY AND THICKNESS VARIATION OF TILES
USED IN 20-CELL STACK

Tile & Mix No.		Density	Thickness Variation
349	457	95.6	0.005
355	461 A	97.1	0.0036
358	458	97.0	0.0025
360	458	96.8	0.0017
361	458	98.4	0.0032
362	458	97.0	0.0026
363	461 B	98.0	0.0033
364	461 B	97.7	0.0021
365	461 B	97.3	0.0028
366	461 B	98.1	0.0027
367	461 B	96.5	0.0028
368	461 B	96.5	0.0025
369	475	97.0	0.0027
370	475	98.5	0.003
373	475	98.3	0.0062
372	475	97.9	0.0031
374	475	98.5	0.003
375	475	98.9	0.0033
376	475	98.2	0.0031
377	475	97.7	0.0032
	Average	97.55	Average 0.0031

In view of the poor performance of six of the cells used in the prior 20-cell stack tested in RP114-2 which had improper electrolyte composition (1), tile mixes were analyzed prior to molding tiles. Chemical analysis of tile mixes identified in Table 2-1 are shown in Table 2-2. All batches were within design specification.

Table 2-2
ANALYSIS* OF TILE MIX BATCHES USED TO MAKE TILES
FOR 20-CELL STACK

	Electrolyte				
	Total	Li_2CO_3	K_2CO_3	$LiAlO_2$	Total
Theoretical	61.8	28.8	33.0	38.2	100.0
Batch 457	60.7	29.8	31.0	35.0	95.7
Batch 461 A	62.9	30.7	32.3	34.9	97.8
Batch 458	65.3	29.0	36.3	36.4	101.7
Batch 461 B	62.5	30.1	32.5	37.2	99.5
Batch 475	62.9	29.9	33.0	36.7	99.6

*Weight percent.

Anode Fabrication

In addition to developing and verifying a reproducible anode fabrication process, a secondary objective of this effort was to demonstrate a manufacturing capability at United for this component. Having this capability would allow a shorter turnaround time on process control improvements resulting in reduced program

costs. Success would also provide a backup source for fabricating stack components.

The approach to meeting the fabrication requirements of the anode was to adapt existing facilities for sintering this powder metal part to a target specification provided from Subtask 1.2 defining materials, total porosity, mean pore size, component dimensions and allowable manufacturing tolerances. Process variables were adjusted as necessary to yield parts which met the specifications.

Anode process development was relatively straightforward. Sintering trials were conducted in a controlled atmosphere belt furnace using an atmosphere of 20 percent hydrogen and 80 percent nitrogen having a dew point less than -20°F. Inco nickel powder type 287 was blended with stabilizer powder and sifted onto the carrier plate at a measured weight and density. This density was selected so that after sintering and rolling to final thicknesses the anode met the specification shown below:

	Total Geometric Porosity	Mean Pore Size
Specification	≧ 65%	3-5.5 μm
Product (typical)	65%	4.2μm

Samples of these anodes were run in 4-inch by 4-inch single cells for longer than 1000-hours with acceptable performance. Post test analysis showed them to be stable under cell operating conditions. Following this verification testing, a set of anodes was fabricated for the 20-cell stack. Thirty-eight parts representing a 90-percent manufacturing yield were made available for stack assembly.

Cathode Fabrication

A secondary objective of this effort was to demonstrate a manufacturing capability at United for this component for the same reasons as given above. The approach to meeting the fabrication requirements of the cathode was similar to that used in fabricating the anode. A target specification was again provided from Subtask 1.2 defining materials, total porosity, mean pore size, component dimensions, and allowable manufacturing tolerances. Unlike the relative ease with which the

anode process was resolved, cathode fabrication presented a more complex set of process variables. The requirement for nearly absolute flatness of the reinforcing screen, on which the nickel powder was deposited and sintered, paced the development work.

Several attempts were made to anneal and flatten the type 316 stainless-steel screens, including the use of a conveyor belt furnace and a retort furnace for annealing in both 20-percent and 100-percent hydrogen at various temperatures. Dead-weight loading was used on screens placed between flat stainless plates for the furnace heat-treating cycles. Acceptable flatness was achieved using a retort cycle at 1400°F with the screens individually sandwiched between flat stainless plates coated with a parting compound and dead-weight loaded to apply pressure. A pilot run was then conducted, yielding cathodes which met specification. The measured properties were as shown below:

	Total Geometric Porosity	Mean Pore Size	Powder
Cathode Specification	≧ 70%	8-12 μm	-----
Sample #3	76%	9.3	#287
Sample #5	73%	7.2	#255

The nickel powder used in preparing sample number three more closely matched the specification and was selected to make parts for 1000-hour 4-in. by 4-in. single cell evaluations. Performance and endurance characteristics of cells using this type cathode were acceptable. Following this verification testing, a set of cathodes was manufactured for the 20-cell stack. Twenty-four parts representing a 60-percent manufacturing yield, where non-recurring development losses are not included, were made available for stack assembly.

Separator Plate Fabrication

The objective of this effort was to develop the materials and joining processes required to fabricate the separator plates for the 20-cell stack. The plate design provided by Subtask 1.2 consists of a stainless steel sheet joined to stainless steel side-rails which form the sealing edges of the plate. The fabrication approach used existing welding technology for joining, and used aluminizing to provide corrosion protection of the rails. The work accomplished is described in the following paragraphs.

Laser and electron beam welding were investigated as preferred methods of joining the sheet and rails. These welding techniques have the advantage of a small heat affected zone thus allowing parts with differing thermal masses to be joined. Metallography of welded sheet coupons 0.012-inch thick joined to rails 0.125-inch thick showed excellent penetration with small heat affected areas using either method. Scale-up trials using sample sizes of 12-inch lengths showed, however, the marked superiority of laser welding. Sheet distortion was minimal compared to electron beam and the laser procedure does not require the use of a vacuum chamber.

A one-square foot separator plate assembly was later welded flat, rigid and free of ripples. In fabricating this plate it was noted that the rails, which were sheared from a larger sheet for this initial trial, had enough twist in them to require heavy clamping pressure to flatten them. To eliminate this and any subsequent problem that might arise during stress relieving, all future rails were machine cut.

In the seal areas, rail corrosion protection is accomplished by aluminizing using a procedure demonstrated on earlier cell and stack components under RP114. Corrosion testing, indicated that the welds also had to be protected from the electrolyte, necessitating that aluminizing be done as a final step in the fabrication process.

The separator plate was supported during the aluminizing temperature cycle by a set of spacer plates equal in thickness to the rails. Despite this fixturing the rails bowed in excess of the design limit. A final annealing-cycle in a belt furnace with the plate and spacers under a dead-weight load corrected this discrepancy. It is believed that this final anneal can be combined with the aluminizing heat-treat cycle in future trials by the use of improved fixturing.

A cell voltage pin is attached to one corner of each separator plate by arc welding.

Separator plates were successfully fabricated for the twenty-cell stack. Twenty-two of the thirty plates fabricated met the squareness specification of ±0.010 inch and all parts met bow and rail spacing specifications. Final inspection showed bow to be from 0.002 to 0.024 inches; design specifications called for 0.050 inch or less.

SUBTASK 1.2 - STACK DESIGN

The objective of this subtask was to design a 20-cell stack of one-square-foot cells with the features required of a 200-cell (20-kW) stack for the breadboard system test to be carried out in Task 3.

A conceptual design study made under the United funded program conducted in parallel with RP114-2 established the requirements for a cost effective full-size stack. Where possible, the design of the 20-cell stack incorporated the features of that conceptual design, such as external manifolding of both reactant gases, fixed-height compressive loading system, and laser welding of separator plates, which were consistent with development results up through the end of this design effort. New component materials and fabrication processes were also used, based on experience gained from previous 8-cell and 20-cell stack tests conducted in Project RP114.

One purpose of testing the 20-cell stack in Subtask 1.5 was to verify that the new design features were suitable for use in the 200-cell, 20-kW breadboard stack. The new design features included in the 20-cell stack were:

- External reactant manifolds.
- Manifold seal and insulator materials.
- Fixed compressive loading system.
- Laser welded separator plates.
- Anodes and cathodes fabricated by United.
- Tiles with provisions to provide thermal cycling capability.
- Containment vessel with inert gas purge.

The selection of these design features are discussed in the following paragraphs.

Design of the Reactant Distribution System

Individual cells in a stack will receive varying reactant flows depending on the difference in the cross-sectional area of the flow channels within each cell. This difference is caused by dimensional variations in the cell package components. In addition, if the manifold depth is too shallow, cells located further away from the inlet and outlet distribution piping would receive less flow than the remaining cells. Therefore, the distribution of reactant flow in a stack was

analyzed to establish the dimensional tolerances for the reactant flow fields within each cell and to determine the depth of the external manifolds.

The reduction of fuel flow to an anode would increase the already high utilization (∿87) percent) required for reasonable system efficiency. Increased fuel utilization will affect the performance of an anode and could result in deleterious effects if the fuel utilization were allowed to approach 100 percent. The analysis of reactant distribution within a multi-cell assembly used a United computer program developed for analysis of acid-cell stacks. This program takes into account expansion, turning losses and gravitational effects of the gases as well as the dominant frictional effect.

Calculations were performed for a one-square-foot, 20-cell stack operating at either 1 atmosphere or at 6 atmospheres pressure and for a 200-cell stack operating at 6 atmospheres.

The results of these calculations are shown in Figures 2-1 and 2-2 as functions of field depth tolerances and manifold size for 20 and 200-cell stacks. Since it is desirable to operate on the flat portion of the curves shown in these Figures, manifold depths of 2 inches were selected for the fuel and oxidant sides of the 20-cell stack. Similarly, manifold depths of 3 inches were selected for the 200-cell breadboard stack. The 20-cell stack design uses center feed and a distribution pipe in the inlet manifolds. The 200-cell stack design uses bottom feed which is predicted to produce a better distribution than center feed for tall stacks. Baffles will be used in the fuel manifolds of the 200-cell stack in order to minimize maldistribution from the effect of natural convection which occurs with increasing manifold size as shown in Figure 2-2. This phenomenon occurs under high pressure operation because the gas is densified and, therefore, moves slowly through the stack. Since hydrogen is consumed producing water and CO_2, the gas in the outlet manifold is heavier than the incoming fuel. By natural convection, the gas in the outlet manifold falls while that in the inlet rises, producing a circulation of gas which increases the gas flow through the top of the stack and reduces the flow through the bottom of the stack. This reduction of flow through the bottom causes the maldistribution curve to rise for large manifold sizes, which results in the minimum shown in Figure 2-2.

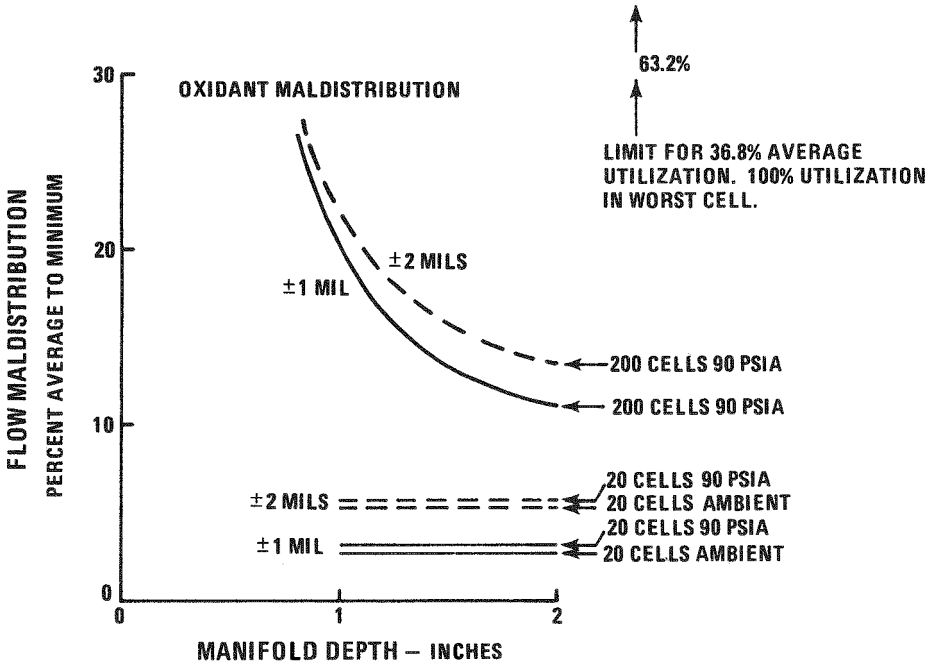

Figure 2-1. Oxidant Flow Maldistribution vs. Manifold Depth

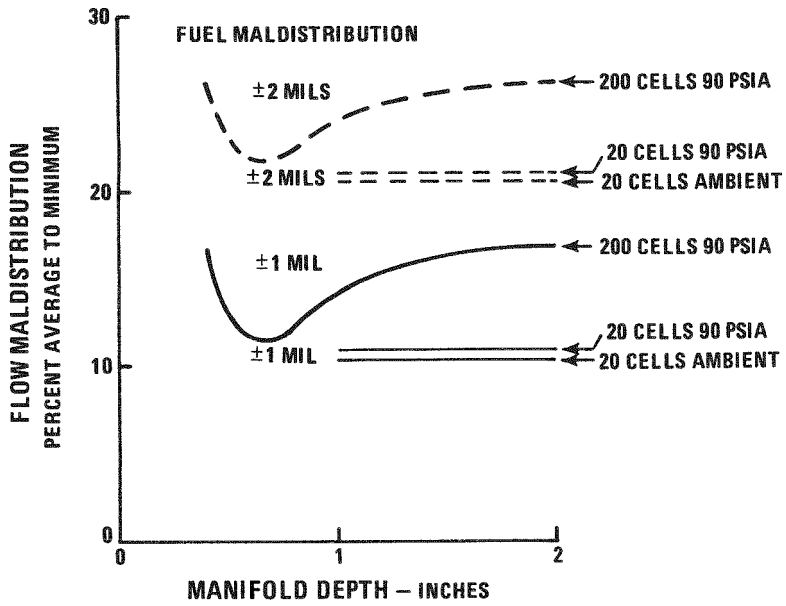

Figure 2-2. Fuel Flow Maldistribution vs. Manifold Depth

The dimensional tolerance calculations in this study were qualitatively confirmed in RP114-2 by measuring the performance loss which occured when the overall fuel utilization of an 8-cell stack was changed from 83 to 20 percent, as shown in Figure 2-3. The cell with the shallowest field height exhibited the largest performance increase. Similar flow maldistribution calculations were made for large-area cell stacks. These studies showed that large manifold sizes were required which made it impractical to consider using internal manifolds. This impracticality was confirmed by cost comparisons between stacks with internal and external manifolds. The cost of a stack using external manifolds was found to be considerably lower. This is the main reason for selecting the external reactant manifolds as the baseline design for large stacks.

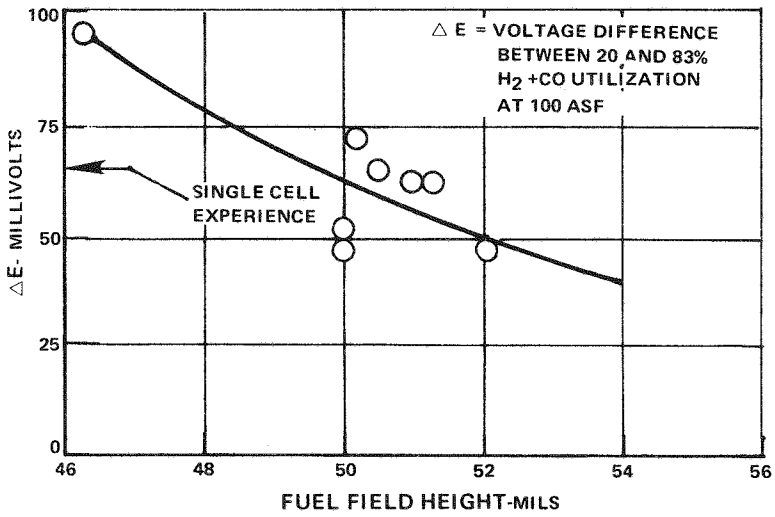

Figure 2-3. Effect of Fuel Field Height on Cell Performance

Design of Manifold Seals

The choice of an external manifold design requires the development of a gasket seal between the manifold and the stack. A detailed study was conducted to establish the requirements for a gasket meeting system and stack requirements.

The leakage of fuel and oxidant from the manifolds into the surrounding canister must be prevented in order to eliminate a fire or explosion hazard. In the present design, this outward leakage will be prevented by keeping the inert gas

in the canister at a higher pressure than the gas in the manifolds. This pressure difference will cause some inert gas to leak through the gasket into the manifolds. The requirement was set on the maximum allowable leakage of this gas. The limiting factor on the leakage rate was found to be the amount of canister gas that could be supplied economically. The effect of leakage on the dilution of the reactants for such a relatively small rate was calculated to be insignificant. When combined with the calculated average pressure drop across the seals, the requirement on the maximum flow rate through the gasket was estimated to be 0.14 lb/h/ft-of-length/ inch-of-water pressure differential.

The efficiency of the seal will be affected by the roughness of the surface of the stack. Estimates of the precision of stacking and the precision of manufacturing the repeat parts were used to set the requirements on surface roughness at ±.005-inch for the inlet manifold sides, which can be aligned against a plane surface, and ±.025-inch for the opposite exit manifold sides.

A theoretical calculation was made of the effect of surface roughness on seal efficiency. This calculation showed that there is an optimum value for the gasket thickness on a rough surface. The existence of such an optimum is understood by noting that if the gasket is very thin it cannot reach down to cover the low spots, but if it is very thick it presents a large cross-sectional area for gas flow.

Figure 2-4 shows that the optimum thickness for the surface roughness specified in the design requirements corresponds to two layers of gasket material on the inlet sides and four layers on the outlet sides, each gasket being nominally .050-inch in thickness. The flows through these gaskets of optimum thickness on a stack with surface roughness within the design tolerances were calculated to be within the design requirements for leakage, and form the basis for an achievable goal which is one-third of the maximum allowable leakage.

The leakage rates with seven layers of gasket material were found to be unacceptably high for the 20-cell stack that was tested in RP114-2. Optimum gasket thicknesses were calculated for the measured roughness of that stack. A second test using the optimum gasket thickness for the measured roughness, plus caulking on some low spots, showed the leakage rate was reduced by a factor of four bringing it within the range specified by the design requirements.

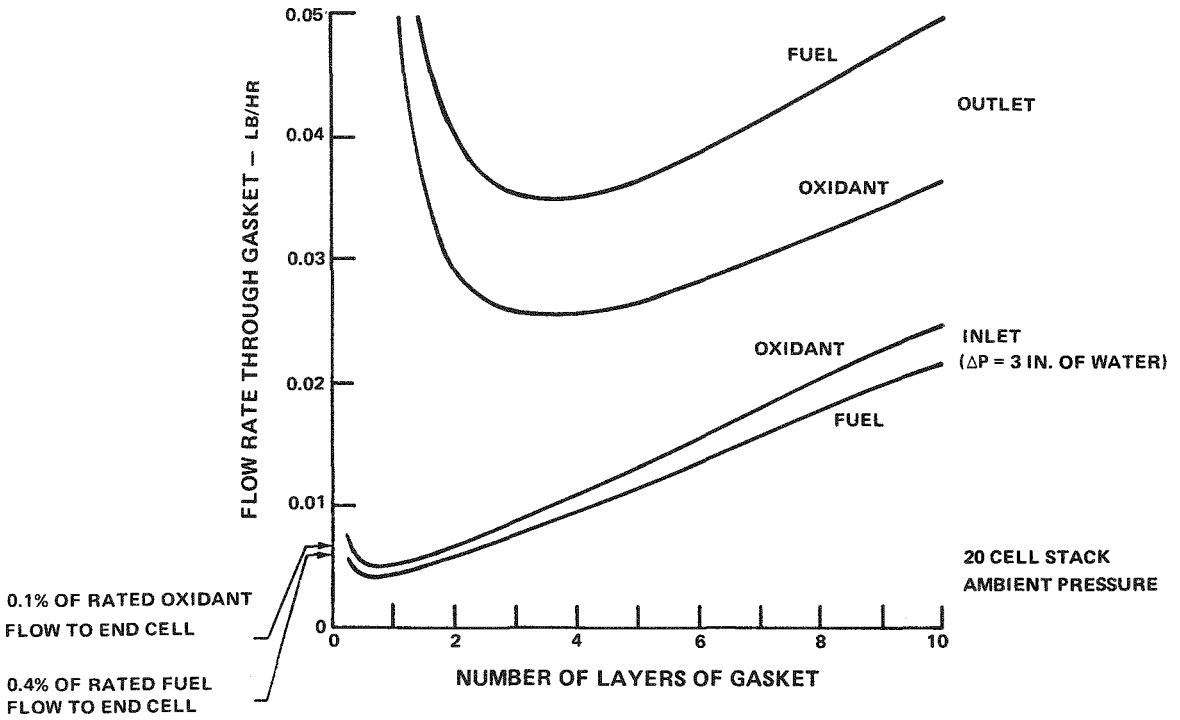

Figure 2-4. Optimization of the Quantity of Gasket Material

An estimate was made of the amount of electrolyte which will be absorbed by the pourous gasket. The calculated electrolyte take-up of the gasket was less than 10-percent, meaning that shunt currents should be low and that the design of the manifold gasket should be satisfactory to meet this requirement as well.

Design of the Compressive Loading System

The compressive loading system maintains force on the stack repeating components to insure adequate electrical contact and effective gas sealing. If a constant compressive load force is used, then the height of the stack decreases as the stack components creep. Since the manifold height does not change, this type of loading system would require a sliding manifold seal. A fixed height compressive loading system was selected for this stack design to maintain the stack at constant height after the load has been applied, thus reducing the need for a sliding seal. One disadvantage of this design is that the load will decrease with time.

In tests to determine if load reduction has a detrimental effect, the follow-up pressure on a 4-in. by 4-in. cell was reduced from 50 to 15 psi. No changes in

cell voltage, internal ohmic resistance, or gas leakage through the edge seals were detected. This test was repeated on a stack of one-square-foot cells with loads between 55 psi and 23 psi with the same results. These tests show that the proposed loading system would not have a detrimental effect on stack operation within a wide range of compressive loads. Further investigation of this issue for long term operation of the commercial configuration is underway.

The tierods and end plates of the compressive loading system were designed to be much stiffer than the stack, thus keeping the stack height constant. The tierods are placed inside the insulation where their temperature will be nearly the same as the temperature of the stack. In this manner, the stack, tierods, and manifolds will expand upon heatup at a nearly constant rate since the materials for the tierods and manifolds were chosen to provide nearly the same thermal expansion coefficients, thereby reducing manifold slide to an acceptable level (less than 0.3-inch for a 200-cell stack).

Two acceptable combinations of tierod and manifold materials were found. The first combination is an iron based superalloy called Tinidur A286 for the tierod together with stainless steel 321 for the manifolds. The other combination is Waspaloy for the tierod and stainless steel for the manifolds. Detailed calculations of the thermal expansion and the sharing of the strain between the stack and the tierods revealed that the Tinidur/SS321 combination was the best overall choice. Actually, the Waspaloy/SS430 combination would produce a smaller manifold slide over the range of operating temperature, but analysis showed that the Tinidur/SS321 combination would keep the load on the stack more nearly constant since Tinidur has higher oxidation resistance, strength, and creep resistance. Calculations indicate that the loss of load due to creep of the Tinidur tierod is only two psi over an operating life of 40,000 hours.

In order to simulate full-size stack behavior in a smaller 20-cell stack, it is necessary to use proportionally smaller diameter tierods. Calculations show that the use of 5/8-inch diameter tierods will simulate the stress/strain behavior of a full size stack with 1-inch diameter tierods. Load relaxation tests were also made on individual tiles of the type used in the 20-cell stack test. These tests indicated that, at constant deflection, the load decreases from 50 to 33 psi in 80-hours at 1200°F. This rate of load dropoff is less than the design limit for this period, since a retorque at 100 hours is planned.

The corner tie rod load on the stack causes the end plates to bend slightly at the edges resulting in uneven distribution of the load across the plan area of the stack; thicker end plates would allow less bending to occur and the distribution of load would be more uniform. The acceptable load variation is not known, but in order to prevent the load from varying by more than 10-percent across the stack, it was determined that the end plates should be two-inches thick for a stack of one-square-foot cells.

Heat Transfer Analysis

A heat transfer analysis was made of the stack design in order to determine insulation requirements. It was concluded that six-inches of insulation on the stack would be satisfactory. At this thickness, heat loss through the end plates results in the predicted temperature distribution shown in Figure 2-5. The top cell operates at an average temperature 7°F cooler than the center cell. This should result in a performance loss in the end cells of only 4 mV at 160 ASF compared to cells in the center of the stack. An analysis was also completed of the heat loss from the inlet piping as it passes through the vessel. The bellows heat-dam selected for the penetrator design was found to be satisfactory since the amount of heat leak from the piping to the vessel base was calculated to be negligible. Insulation thicknesses of three inches on the fuel lines and six-inches on the oxidant lines were specified for the piping, both inside and outside the vessel.

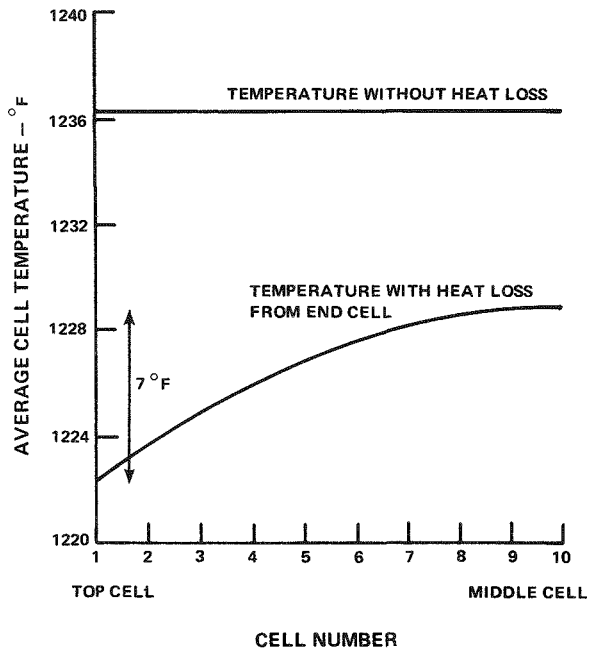

Figure 2-5. Predicted Temperature Distribution in 20-Cell Stack

Design of Power Takeoff and Manifold Voltage Protection

The power takeoff bars were designed to be made of a manganese-nickel alloy because of its high conductance, high temperature capability and oxidation resistance.

The stainless steel manifolds are coated with aluminum oxide to dielectrically isolate them from the side of the stack. These manifolds are electrically connected to the positive end plate through a fused circuit with an ammeter which will indicate the presence of a short in the event of a coating break-down. The end plates and tie rods are also electrically connected to the positive end of the stack. This is the best choice for the manifold potential because if shunt current bridging is encountered, the manifolds and not the stack become the sacrificial electrodes. The ammeter permits early identification of shorting to allow corrective action prior to stack damage if break-down does occur.

Design of Separator Plate

The use of external manifolds on the stack simplifies the design of other cell parts. In particular, the design of the separator plate is reduced to a square of sheetmetal with four bar flanges attached as shown in Figure 2-6. Several methods of joining these flanges to the sheet were compared. These methods included brazing, resistance welding, electron beam welding and laser welding. Laser welding was found to be the most cost effective process because of its high speed manufacturing capabiltiy.

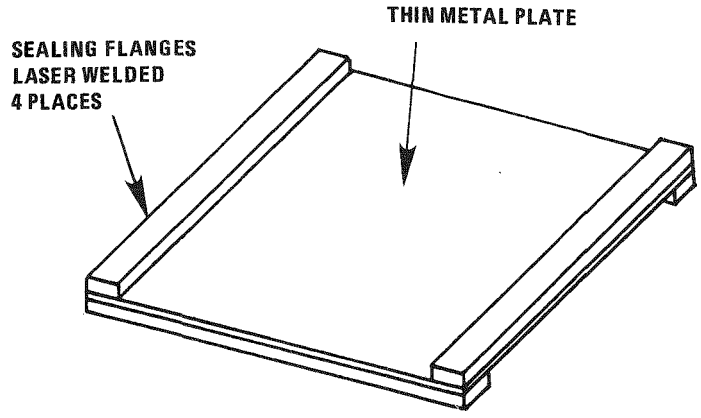

Figure 2-6. Separator Plate Sealing Flange Arrangement

Flatness Requirements

A study of the flatness requirements for the cell components concluded that the separator and electrolyte tiles could not be out of plane by more than .050-inch to prevent cracking the tiles during stack assembly, and also concluded that the load required for flattening would be a small fraction of the total load. Inspection of the tiles fabricated for the 20-cell stack showed that the .050-inch flatness requirement was achieved easily using present tile manufacturing procedures. A tile thickness variation of ±.002-inch was specified to promote effective sealing on the edges of each cell.

Instrumentation

Instrumentation requirements for the stack were established. Provision was made to determine individual cell voltages and to measure stack termperatures at 16 positions in the stack, at six positions in the manifolds, at four places along the compressive load system, and at two positions in the vessel. A hydrogen sensor for the containment vessel was specified as a safety measure. High temperature strain gauges were used on each tierod to measure the compressive load.

Electrolyte Management

An estimate was made of the inventory of electrolyte required for stack operation as a function of time at rated power. The estimate included a prediction of the electrolyte loss due to evaporation and corrosion. Figure 2-7 shows that the estimated operating time before refill is between 2500 and 3100 hours, assuming rated power reactant flows for a conventional steam reformer system at 14.7 psia. If the stack is operated with rated-power flow rates for an adiabatic reformer system, the time before refill is estimated to be 2100 to 2600 hours. The time before refill is extended if the stack is operated at flow rates less than rated power or at pressures higher than 14.7 psia. For example, if the stack is operated as planned, being at rated power with steam reformer reactant flows for the first 1000-hours and then being at 65 psia with rated power adiabatic reactant flows, the predicted time before refill increases to of 3100 to 3700 hours. The predicted time before refill is still higher if the stack is operated at either less than rated power or at higher pressures. Electrolyte which is lost by vaporization will be trapped by electrolyte scrubbers downstream of the exit manifolds.

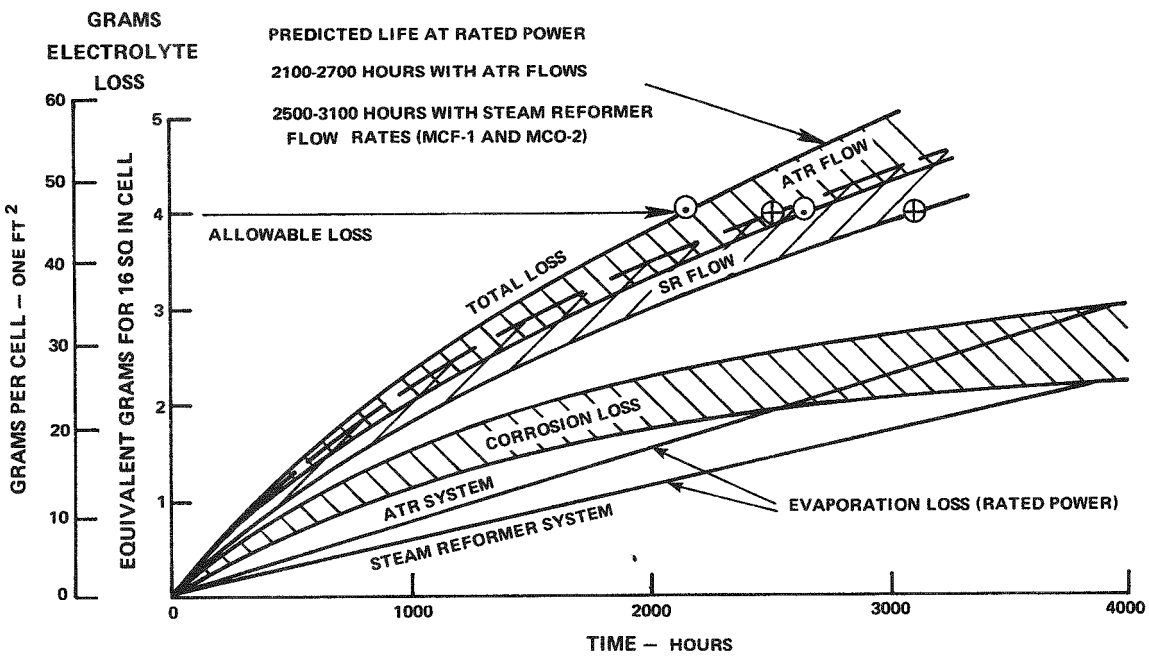

Figure 2-7. Predicted Electrolyte Loss

Construction Drawings

The detail drawings of all parts of the 20-cell stack were completed and stack assembly and loading procedures were specified. The completion of this work concluded the design effort in Subtask 1.2.

SUBTASK 1.3 - ESTIMATE STACK PERFORMANCE AND DEFINE TEST OBJECTIVES

This Subtask provided an estimate of the performance and a statement of the objectives for the Task 1 20-cell stack tested at ambient pressure. The purpose of this test was to assess the performance, endurance, and restart characteristics of the Subtask 1.2 stack design.

Test objectives were:

1. To demonstrate performance and endurance characteristics comparable to subscale cells of the same design (Table 2-3).

2. To demonstrate reactant gas containment within the limits of pressures differential and leak rate established by the Subtask 1.2 stack design (Table 2-4).

Table 2-3

PREDICTED STACK PERFORMANCE*

Cell Voltage at rated current density:	0.71 V/C @ 160 ASF
Cell Current density at rated voltage:	104 ASF @ 0.785 V/C
Cell Power density at rated voltage:	82 WSF @ 0.785 V/C

(125 WSF at rated voltage was assumed in reference system design)

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* Performance on reactant gas compositions and utilizations associated with the ambient pressure RP-114 reference system design, simulated as follows:

Fuel gas - 50.9% H_2, 9.9% CO, 10.7% CO_2, 28.5% water. Fuel Utilization (H_2 consumed/H_2 + CO feed in moles) equals 83%. Oxidant gas - 17% CO_2, 63.8% N_2, 11.7% O_2, 7.5% H_2O. CO_2 Utilization equals 30%. Ambient pressure, average temperature 1200°F. Flows are always set for 160 ASF at the utilizations noted. Utilization varies proportionally for other current densities.

Table 2-4

PREDICTED MANIFOLD SEAL LEAKAGE

Oxidant Manifolds:		
Inlet	-	0.007 pph
Exit	-	0.026 pph
Fuel Manifolds:		
Inlet	-	0.006 pph
Exit	-	0.035 pph

These exchange rates would have an insignificant effect on system efficiency

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3. To demonstrate a multiple restart capability using the requirements imposed by objectives 1. and 2. as criteria for success.

4. To demonstrate satisfactory mechanical and operational characteristics of the stack compressive loading system, and the thermal and electrolyte management approaches (Table 2-5).

5. To demonstrate an approach to effective carbonate vapor scrubbing from stack reactant exhaust gases (Subtask 1.6).

Table 2-5

PREDICTED ELECTROLYTE LOSS

Worst case electrolyte loss could limit useful operating life to:

2100 to 2700 hours

Assumptions

-- 54 g/ft^2 electrolyte inventory at beginning of life

-- End of useful life occurs when anode electrolyte is reduced to 18 g/ft^2

-- 30% prefilled anode at BOL and 10% fill at end of useful life

-- Rated power flow rates of RP1273 conceptual design for ambient pressure operation

Expected Operation will extend useful life:

-- Ambient operation will be at lower flow rates associated with conventional steam reformer gases

-- Flow rates associated with adiabatic reformer gases will be used only at pressure

The performance estimate shown in Table 2-3 was constructed using data obtained from the fourteen typical cells tested in the last RP114-2 stack. These data are shown in Figure 2-8. Equivalent performance was expected from all cells in the stack tested in Subtask 1.5.

The reactant-gas leakage estimate shown in Table 2-4 was made using component test data and design studies conducted in Subtask 1.2. The projected leak rate curves for a 20-cell stack were shown in Figure 2-4 as a function of the number of layers of gasket. The leakage predictions in Table 2-4 assumed the use of two layers of gasket for reactant inlet manifolds and four layers of gasket for reactant exit manifolds.

The electrolyte loss estimate loss to predict the stack life shown in Table 2-5 was based on electrolyte loss measurements on subscale cells and vapor pressure data obtained in the laboratory. These data for various operating conditions of the stack were shown in Figure 2-7. The life prediction in Table 2-5 assumed the worst case electrolyte loss rate.

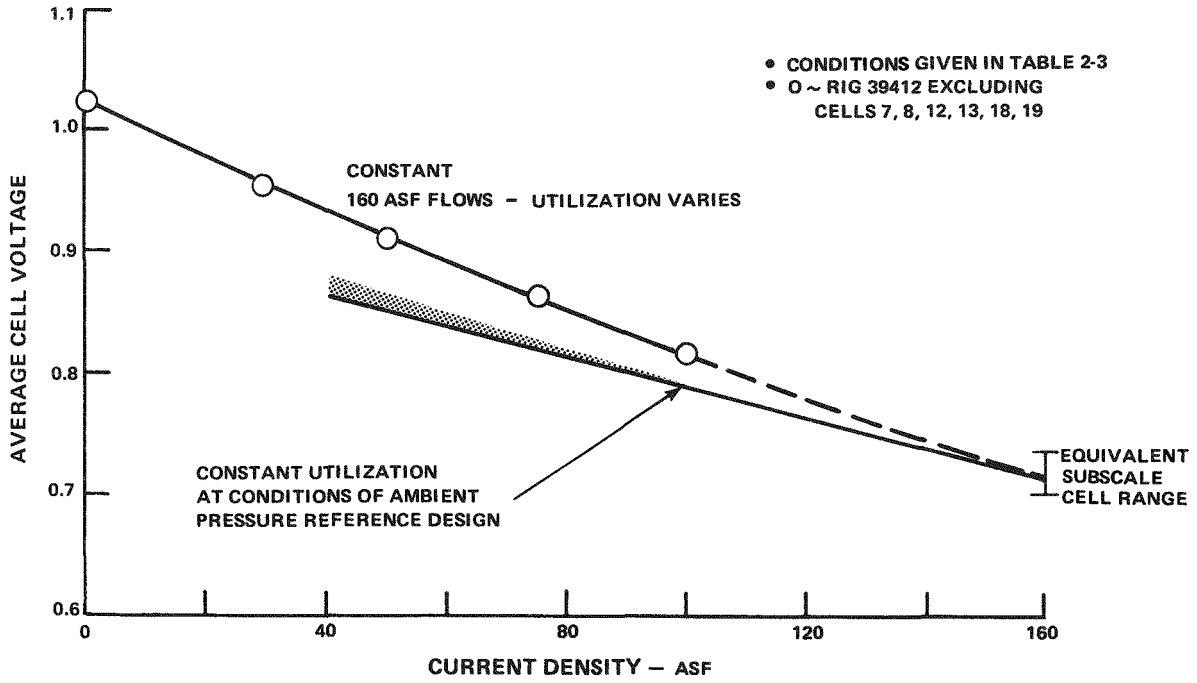


Figure 2-8. Predicted Cell Performance

Planned testing for the Task 1 stack includes approximately 1000 hours of ambient operation being followed by approximately 1000 hours of pressurized operation (>65 psia) and a total of six thermal cycles. Off-design testing was to be defined after ambient testing was complete.

SUBTASK 1.4 - FABRICATE 20-CELL STACK

This subtask provided for the fabrication and assembly of the 20-cell stack.

All of the non-repeat stack hardware designed in Subtask 1.2 including the axial compressive load system, reactant manifolds, instrumentation, vessel penetrators, etc., were fabricated and made ready for stack assembly. Assembly preparations also included the adaptation of a surplus acid-stack pressure vessel for molten carbonate stack operation. The redesign of this vessel's penetrator layout was completed in Subtask 1.2, and the needed modifications were made. This vessel will permit stack testing to be conducted at pressures up to 65 psia. As reported under Subtask 1.3, the test plan for the Task 1 20-cell stack includes 1000 hours of pressurized operation once the test facility being constructed in Task 2 is complete.

Figure 2-9 shows the 20-cell stack assembly prior to having the reactant manifolds installed. Figure 2-10 shows the finished stack as it was being mounted on the base plate of the containment vessel, and also points out the primary design features of the stack non-repeat parts and ancillary components evaluated for the first time in a molten carbonate stack. These new features were:

- External manifolding of both reactant gases.
- Fixed height compressive loading system.
- Electrolyte vapor scrubbing scheme.
- Pressure vessel penetrator couplings.
- Containment vessel with inert gas purge.

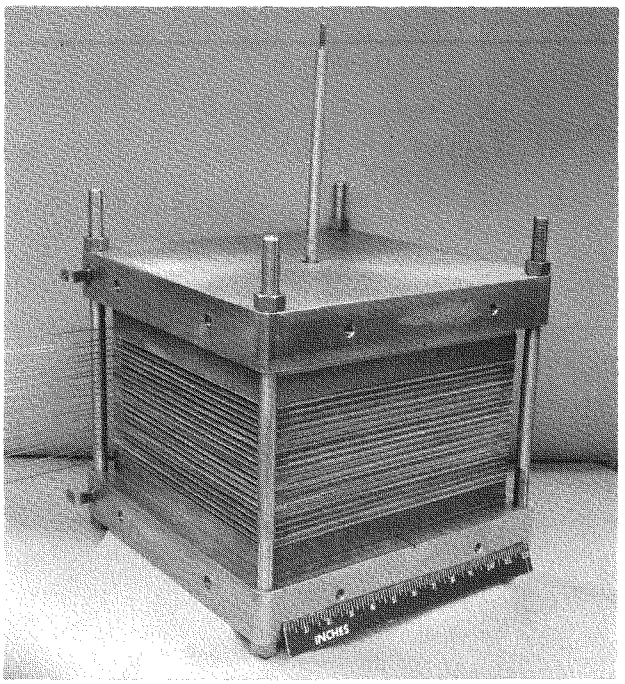


Figure 2-9. 20-Cell Stack Assembly

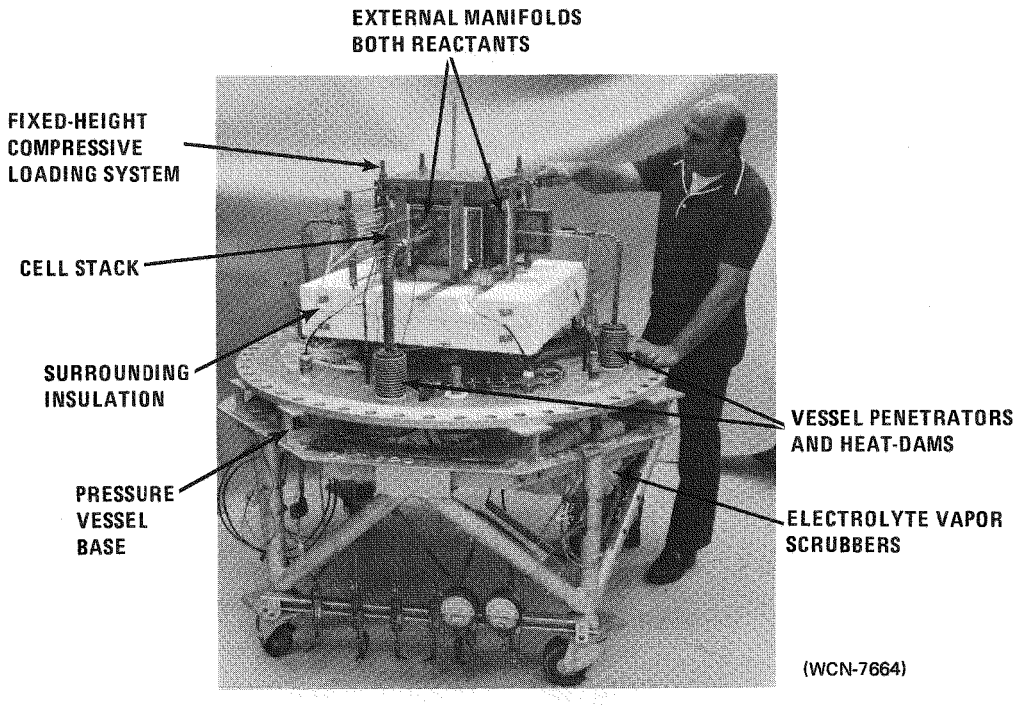


Figure 2-10. 20-Cell Stack Mounting on Vessel Base

SUBTASK 1.5 - STACK TESTING

This Subtask provided for testing the ambient pressure 20-cell stack in Task 1 and included refurbishing and retesting a 20-cell stack from RP114-2 in order to investigate possible rebuild techniques. This rebuild is discussed first.

16-Cell Stack Rebuild and Test

The refurbishment and retesting of the 20-cell stack from RP114-2 was completed. That stack had been tested for over 2000 hours with six cells that were deficient in electrolyte and, therefore, were performing poorly. Deficient cell replacement was undertaken in this Subtask to investigate possible replacement techniques.

The six electrolyte deficient cells (7, 8, 12, 13, 18, and 19) were removed from the stack in adjoining pairs and replaced with one new cell per pair. One of the previously good cells (Cell 20) was damaged during the removal of Cells 18 and

19, and was also omitted from rebuild. The resulting 16-cell stack was reassembled with Cells 7, 11, and 16 (renumbered), being the replacement cells. The 16-cell stack test was also used to evaluate a zirconia manifold seal material which chemical compatability tests showed superior to the previously used aluminum oxide, while necessary structural and gas-permeability characteristics were similar. The replacement material was also applied to the manifold seal flanges for dielectric protection. Chemical degradation and spalling of the aluminum-oxide coating previously used was responsible for the loss of dielectric strength and cell shorting experienced in the operation of the original 20-cell stack.

Upon starting the rebuilt 16-cell stack, the measured reactant gas leakage was low and comparable to that recorded on the stack prior to rebuild. This is shown in Figure 2-11 which compares fuel leakage on a per-cell basis prior to shutdown of the 20-cell stack and upon restart of the refurbished 16-cell assembly.

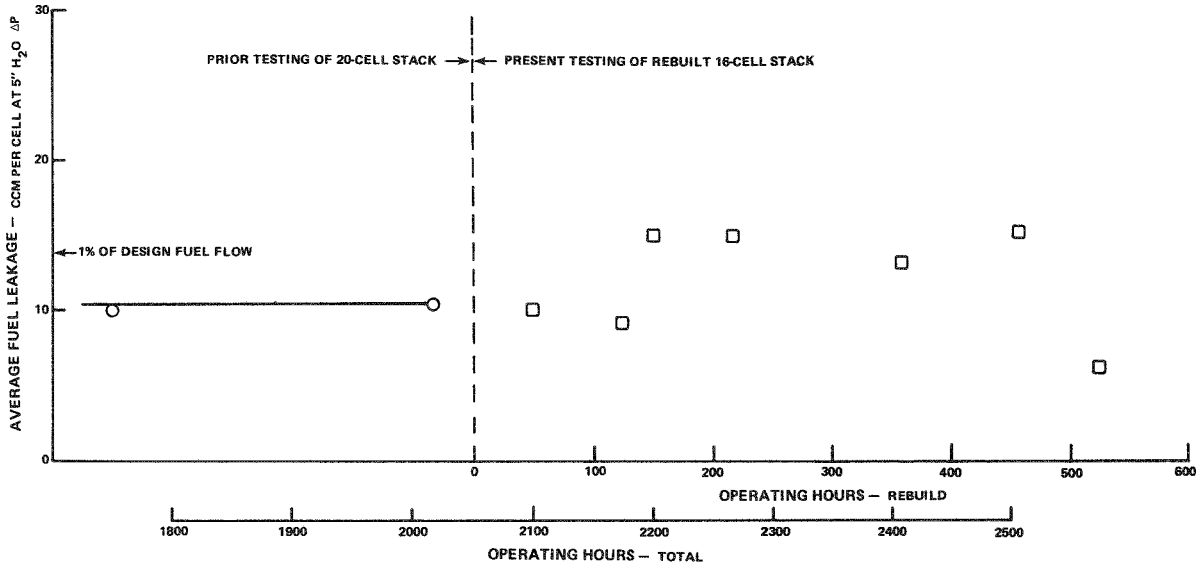


Figure 2-11. 16-Cell Stack Fuel Leakage Comparison

Upon operating the stack, Cell 16 was found to be performance limiting at 0.7 volts and 30 amps-per-square-foot (ASF). Figure 2-12 shows that the problem with this cell, and with the other two replacement cells as well, was a higher than normal internal resistance (iR). Although the iR of the replacement cells gradually diminished with corresponding improvements in cell voltage over the first 200 hours of operation, Cell 16 remained significantly lower in performance than the remaining cells.

CELL NUMBER	FINAL 20-C STACK DATA IR V/100 ASF	OPEN CIRCUIT	V @25 ASF	INITIAL 16-C REBUILD DATA IR V/100 ASF	OPEN CIRCUIT	V @25 ASF	300 HR 16-C REBUILD DATA IR V/100 ASF	OPEN CIRCUIT	V @25 ASF
1	.114	.970	.919	.331	.966	.817	.176	.892	.829
2	.084	.985	.941	.117	.971	.881	.097	.946	.890
3	.084	1.001	.955	.117	1.000	.900	.097	.970	.911
4	.089	1.004	.956	.159	1.006	.889	.111	.983	.915
5	.080	1.007	.961	.131	.997	.899	.093	.989	.924
6	.072	1.010	.963	.131	1.006	.901	.093	.996	.924
7	(REPLACED CELL)			.304	1.022	.855	.107	1.013	.927
8	.076	.989	.950	.131	1.018	.908	.104	1.009	.930
9	.072	1.008	.960	.152	1.014	.900	.114	1.006	.925
10	.089	1.022	.965	.117	1.015	.906	.090	1.009	.933
11	(REPLACED CELL)			.539	1.019	.786	.211	1.014	.894
12	.089	1.009	.863	.114	1.017	.894	.114	1.006	.913
13	.076	.987	.960	.124	1.021	.907	.093	1.006	.919
14	.076	1.008	.964	.131	1.020	.885	.107	1.011	.915
15	.072	1.009	.951	.159	1.021	.881	.121	1.009	.917
16	(REPLACED CELL)			.795	1.025	.729	.605	1.018	.805

Figure 2-12. 16-Cell Stack Performance Comparison (at conditions given in Table 2-3)

In-cell diagnostic tests indicated that the high iR of the replacement cells was due to increased resistance loss across oxide layers on the cathode side of the reused separator plates. In order to verify this, a dilute reducing gas was supplied to the stack cathode components for a 24-hour period in order to partially reduce these oxides and promote improved metal-to-metal contact.

When the stack was returned to normal operation, the deficiency in Cell 16 was found to have been partly corrected. The data of Figure 2-13 shows that the voltage and iR of the replacement cells had become closer to those of the reused cells indicating that higher cathode component-to-component resistance was in fact the cause and that an approach to avoiding this resistance increase is needed to assure a successful rebuild.

After returning to normal operating conditions, Cell 1 became the lowest performing cell and declined steadily with continued operation. Figure 2-13 shows that the low performance and steady decay of Cell 1 was due to an electrical short-circuit. This short was confined to this cell only, and resulted in the fuel starvation of Cell 1. The stack was operated at design current density to assess the impact of this situation on stack operation. Short-term stability was not achieved and the test was terminated to allow time to refurbish the stand for the Task 1 20-cell stack test which followed. Total operating time on this stack was 2700 hours, which included 650 hours following the rebuild.

CELL NUMBER	300 HR 16-C REBUILD DATA			DATA DURING REDUCTION CYCLE	DATA FOLLOWING REDUCTION CYCLE		
	IR V/100 ASF	OPEN CIRCUIT	V @25 ASF	IR V/100 ASF	IR V/100 ASF	OPEN CIRCUIT	V @ 25 ASF
1	.176	.892	.829	.114	.142	.815	.703
2	.097	.946	.890	.076	.090	.912	.848
3	.097	.970	.911	.072	.094	.935	.875
4	.111	.983	.915	.072	.111	.957	.877
5	.093	.989	.924	.068	.090	.967	.897
6	.093	.996	.924	.068	.097	.974	.891
7	.107	1.013	.927	.080	.090	1.003	.886
8	.104	1.009	.930	.072	.121	.989	.892
9	.114	1.006	.925	.080	.135	.988	.890
10	.090	1.009	.933	.061	.090	.971	.917
11	.211	1.014	.894	.072	.118	1.007	.846
12	.114	1.006	.913	.065	.135	.968	.876
13	.093	1.006	.919	.061	.111	.985	.895
14	.107	1.011	.915	.061	.146	.987	.873
15	.121	1.009	.917	.057	.911	.984	.848
16	.605	1.018	.805	.080	.188	1.018	.929

Figure 2-13. 16-Cell Stack Effect of Partial-Reduction-Cycle on Cell Performance (at conditions given in Table 2-3)

An analytical study and review of earlier subscale single cell tests indicated that fuel starvation results in the following cell behavior:

- Negative cell voltage (-0.4 to -1.0 volts).
- Evolution of 2:1 molar ratio of CO_2 and O_2 in the anode compartment.
- Oxidation of anode compartment materials.
- A five-fold increase in cell resistance.

Despite these indicators of poor performance, the subscale tests indicated that this type of cell failure (defined as significant power absorption) does not occur in a short time and at least 1000 hours or more of operation are possible without a shutdown.

The effect of negative cell operation on the 16-cell stack are shown in Figure 2-14 where individual voltages at 100 ASF of the first five cells in the stack are plotted versus time. When the load was initially applied, Cells 1 and 2 were at negative voltage and Cells 3, 4, and 5 were at positive voltage. Cell 3 decayed to a negative voltage after one hour and Cell 4 decayed to negative voltage after four hours. The progression of declining performance through the first five cells of the stack is attributed to the current maldistribution caused by the local shorting in Cell 1. Excessive reactant consumption at the short

location resulted in fuel starvation and anode oxidation, which prevented transfer of stack current through a large area of Cell 1. This current shift is transferred to Cell 2 which becomes locally fuel starved, since the current distribution no longer matches the fuel flow distribution and local oxidation of the anode occurs. The limited stack data suggests that the current maldistribution becomes less severe in successive cells until local starvation no longer occurs and that the propogation of cell failure may arrest with time. However, longer term operation is required to evaluate this trend. Test stand availability precluded longer-term endurance evaluation at that time. The 16-cell stack has not yet been disassembled for inspection.

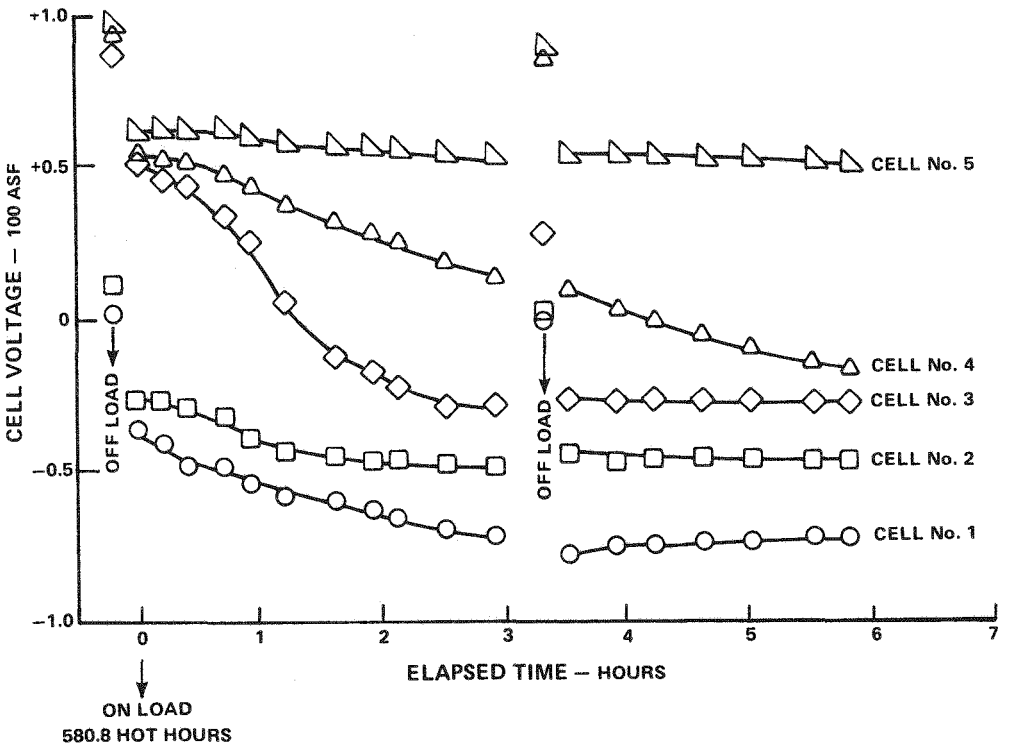


Figure 2-14. 16-Cell Stack Negative Cell Operation
(at conditions given in Table 2-3)

20-Cell Stack Test

Ambient pressure testing of the 20-cell stack was completed following a total of 890 hours at temperature, including approximately 500 hours of load time and one thermal cycle. The test results through this period of testing verified that:

- Sealing of stack reactant gases was within acceptable design limits.
- Operating performance of the stack was within the range of comparable subscale cells.
- Function of the stack containment vessel and associated penetrator fittings were acceptable.
- The pressure drop and temperature control of the carbonate scrubber systems were acceptable.

Figure 2-15 shows that stack performance during the initial period of operation compared favorably to a bench-scale cell having similar components. A more detailed comparison of stack performance to the original test objectives outlined in Subtask 1.3 is presented under Subtask 1.8 of this report.

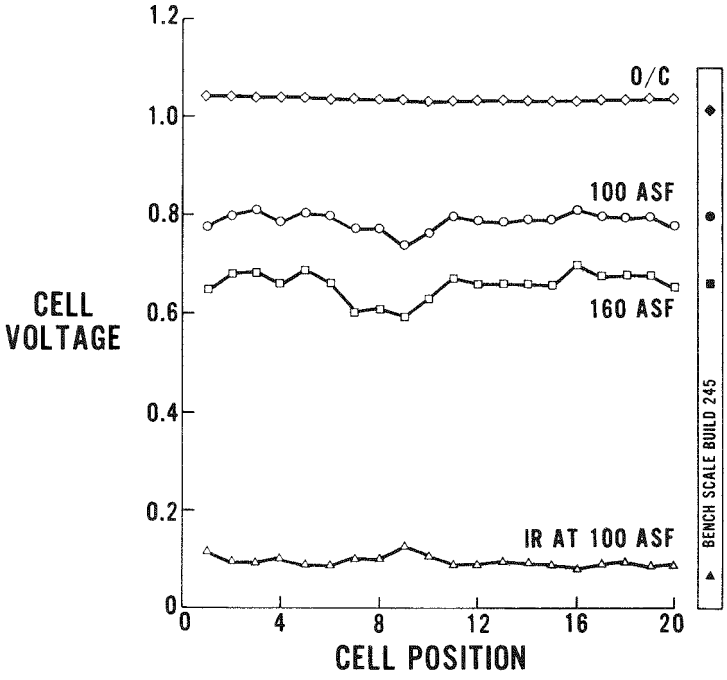


Figure 2-15. 20-Cell Stack Performance Comparison (at conditions given in Table 2-3)

Subsequent to initial performance checks, the stack was thermal cycled. This thermal cycle was originally planned for transferring the stack compressive load from the exterior follow-up system to the internal fixed system, but a cooldown was also necessary to correct a deficiency in the design of the dielectric barrier between the stack and its reactant-gas manifolds. During the initial period of stack operation, new diagnostic procedures showed that the approach being used

to electrically isolate the reactant gas manifolds from the sides of the stack was inadquate. The shutdown for removal and inspection of the stack manifolds confirmed the diagnostic conclusion that ionic paths were connecting cells in the stack and, if left uncorrected, electrical shorting of cells would have occurred at some later time in the test. A more positive dielectric barrier was assembled into the stack manifold seals for test continuation.

Following the thermal cycle, the diagnostics showed:

- No shunt-current between stack and manifolds; confirming the design change.
- No change in stack internal reactant leakage due to the thermal cycle.

Figure 2-16 shows the stack as it was initially started: insulation and full instrumentation were in position, but the dome of the pressure vessel had not been installed. The stack was held on dilute reactant gases in this configuration while setting stack compressive load and insuring adequate gas seals. These were accomplished at approximately 300 hours into the test.

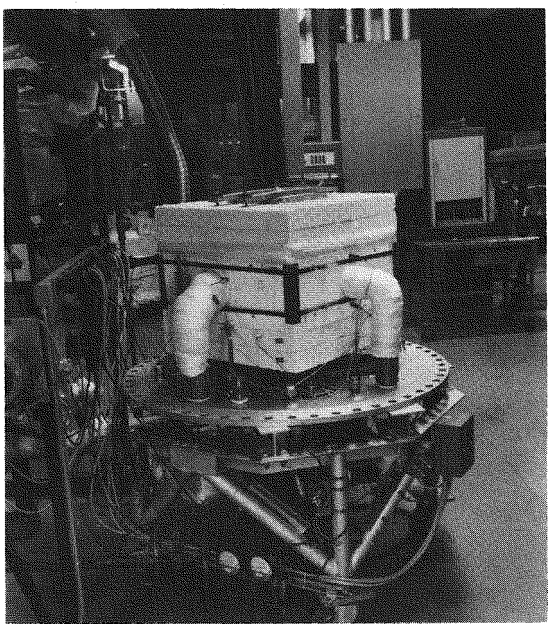


Figure 2-16. 20-Cell Stack-Initial Start-up Configuration

Figure 2-17 shows the stack as it was operated in the containment vessel. The vessel has a test capability up to an operating limit of 65 psia, and although ambient pressure testing was conducted at 15.5 psia, due to the present test stand limit, a continuation of this test is scheduled to be run at elevated pressures once the new stand being constructed in Task 2 is completed.

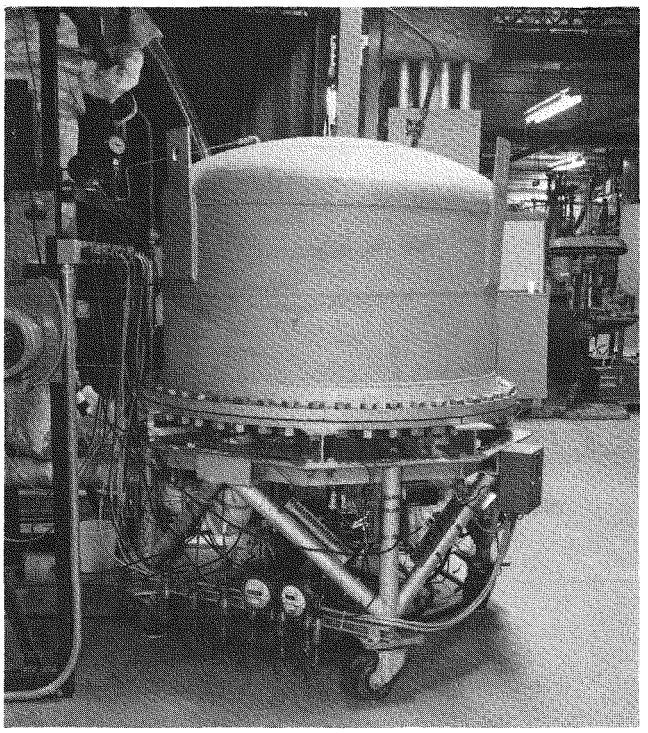


Figure 2-17. 20-Cell Stack Test

SUBTASK 1.8 - COMPARISON OF TEST RESULTS WITH OBJECTIVES

The purpose of this subtask was to evaluate the results of the 20-cell stack test against the objectives defined in Subtask 1.3. The five objectives are restated below:

1. To demonstrate performance and endurance characteristics comparable to subscale cells of the same design.

2. To demonstrate reactant gas containment within the limits of pressure differential and leak rate established by the Subtask 1.2 stack design.

3. To demonstrate a multiple restart capability using the requirements imposed by objectives 1. and 2. as criteria for success.

4. To demonstrate satisfactory mechanical and operational characteristics of the stack compressive loading system, and the thermal and electrolyte management approaches.

5. To demonstrate an approach to effective carbonate vapor scrubbing from stack reactant exhaust gases (Subtask 1.6).

The first four objectives have been addressed for ambient pressure operation. In light of the relatively short program run at ambient pressure on the 20-cell stack, the carbonate vapor scrubbers will be used to accumulate more operating time with an 8-cell stack planned for testing in the parallel Niagara Mohawk program before they are disassembled and analyzed.

The ambient pressure phase of the 20-cell stack test program was completed after a total of 890 hours of hot time and two starts. The test program included:

1. Current-voltage calibrations over a wide range of operating temperatures between 1175°F and 1250°F.

2. Fuel and oxidant utilization sweeps to levels in excess of design to determine operating margin.

3. Periodic iR measurements.

4. Periodic measurements of internal and external reactant gas leakage.

5. Extended operation at 100 ASF to assess performance changes and evaluate materials integrity.

Figure 2-18, showing a current-voltage calibration run to rated power conditions, and a series of test diagnostics indicates the following:

1. Overall initial performance at the 160 ASF rated power point averaged ~0.66 V/C compared to a pre-test prediction of 0.71 V/C (Table 2-3).

2. Lower than predicted performance was due to higher than predicted internal resistance values.

3. The performance was comparable to the level seen on bench-scale control cells built using parts from the 20-cell stack inventory (see Figure 2-15).

4. The internal resistance averaged ~95 mV/100 ASF compared to the 55-60 mV/100 ASF level observed on the 14 good performing cells of the last 20-cell stack tested in RP114-2. This higher iR may be associated with the relatively imprecise location of the cathode support screens in these cells compared to the previous stack.

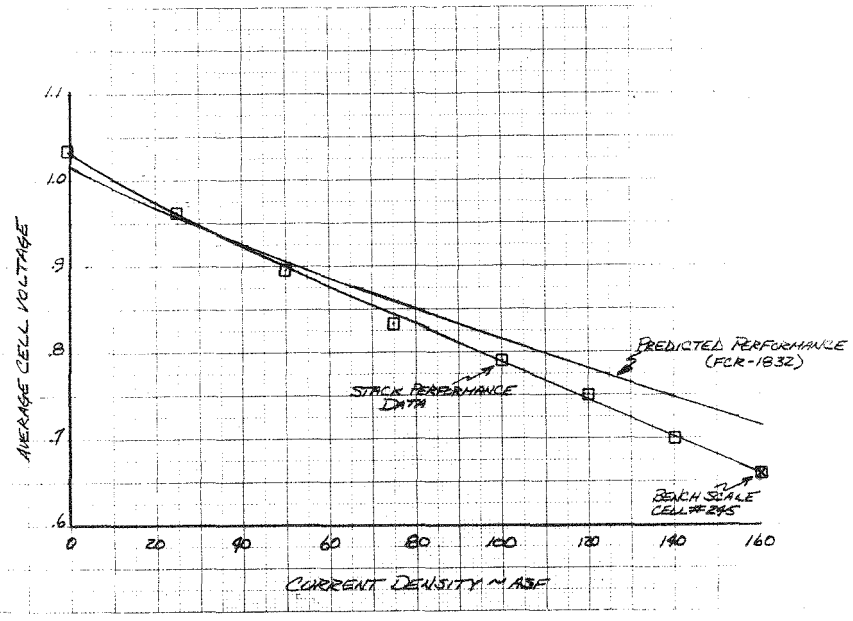


Figure 2-18. 20-Cell Stack Performance Calibration (at conditions given in Table 2-3)

5. There were no cells with excessive fuel or oxidant utilization sensitivity, indicating good reactant gas distribution from cell to cell. Figures 2-19 and 2-20 show individual cell performance response from low-utilization gas flow rates to design and above design utilization levels.

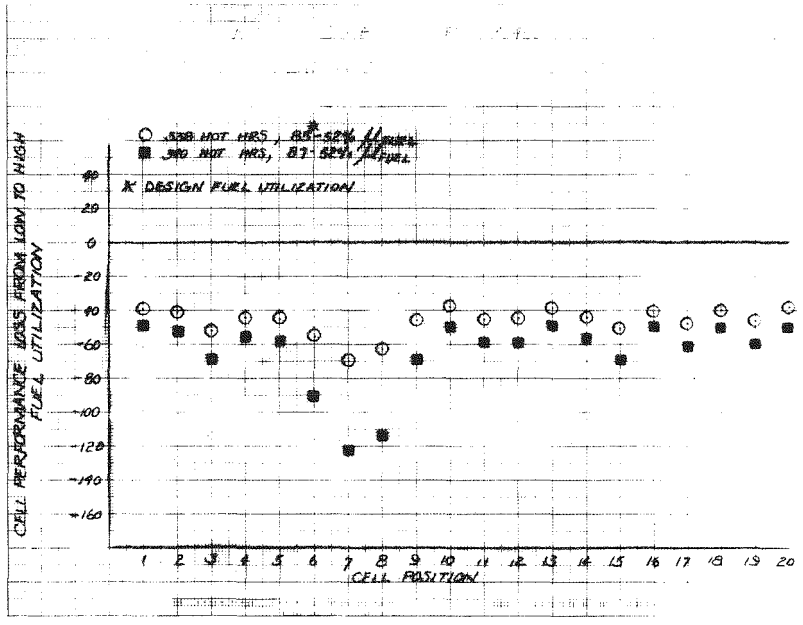


Figure 2-19. 20-Cell Stack Performance vs. Fuel Utilization (all other conditions were as given in Table 2-3)

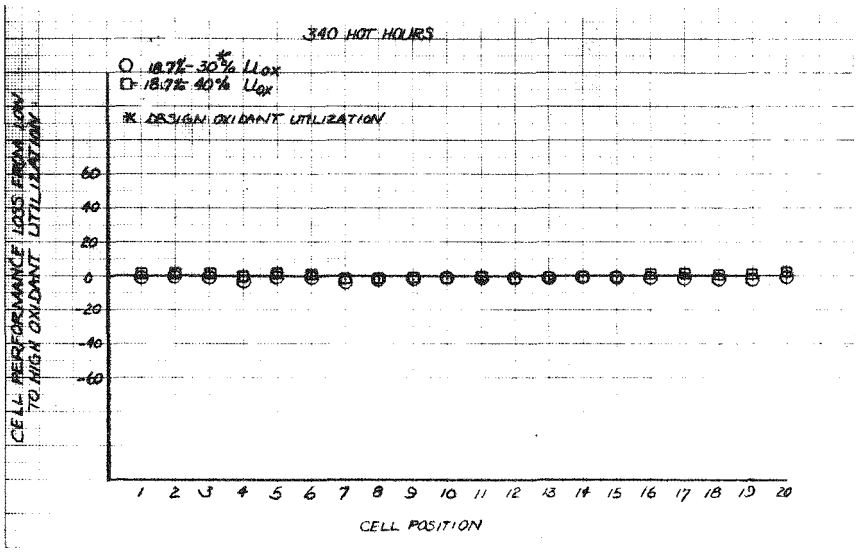


Figure 2-20. 20-Cell Stack Performance vs. Oxidant Utilization (all other conditions were as given in Table 2-3)

6. The stack was capable of operating over an 1175 to 1250°F average temperature range without difficulties. Figure 2-21 shows the influence of temperature on performance at 140 ASF. The temperature influence coefficient of ≅.9 mv/°F was more than twice that observed in typical subscale tests. Other diagnostic data indicated that this influence coefficient was related to the cell internal resistance characteristic, the level of which was unexpectedly high.

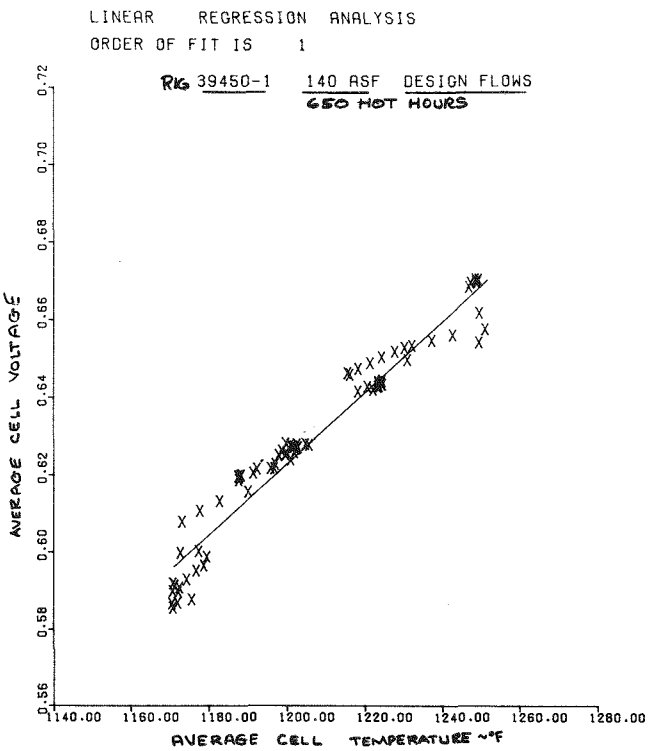


Figure 2-21. 20-Cell Stack Performance vs. Temperature Correlation (all other conditions were as given in Table 2-3)

Figure 2-22 shows the results of stack crosspressure-leakage measurements obtained during the test. These data show that the wet seals improved gradually, but that the 50 psi followup pressure initially used on the stack was inadequate to achieve acceptable sealing within the alloted test period of 200 hours. For this reason the compressive load was increased to 65 psi, the same load used on the previous two stacks tested in RP114-2, and by 300 hours the seals improved to a level permitting design operation. This leakage level remained low for the duration of this test.

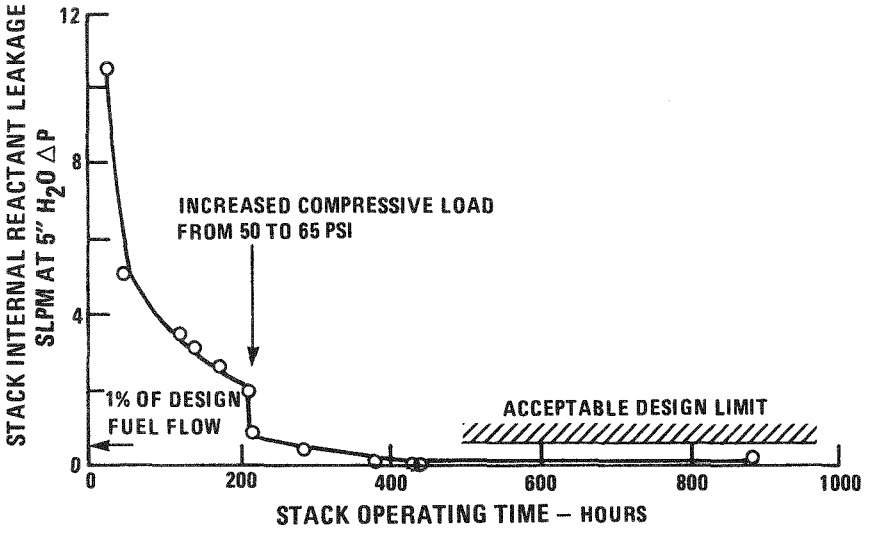


Figure 2-22. 20-Cell Stack Internal Reactant Leakage

Figure 2-23 shows similar measurements of stack reactant manifold leakage. These data were within the design limit prior to the thermal cycle when the addition of improved dielectric barriers within the manifold seals resulted in an increased leakage rate. The design solution which simultaneously satisfies both dielectric protection and seal requirements if being pursued for the retest of this stack at pressure.

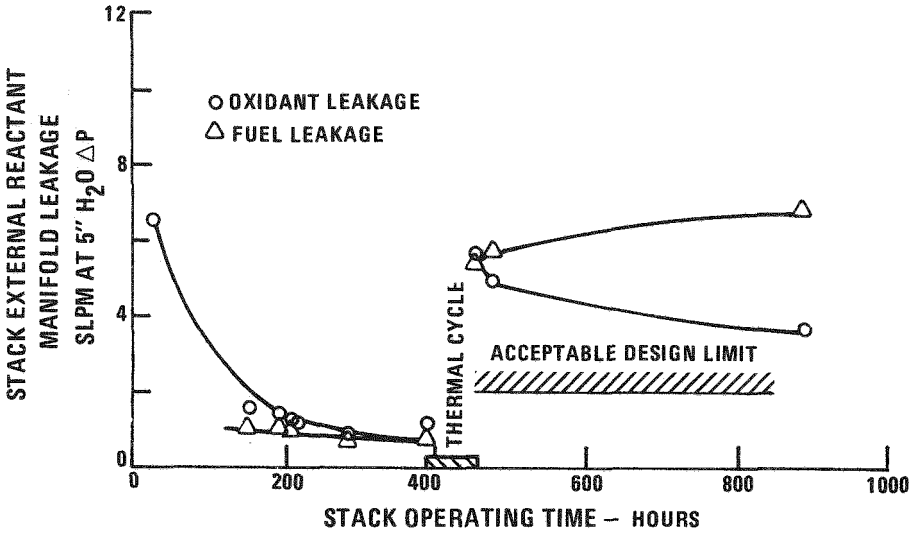


Figure 2-23. 20-Cell Stack External Manifold Leakage

Figure 2-24 shows an annotated performance history of the stack at 100 ASF. This Figure shows that following the initial stabilization period and test diagnostics, the stack was thermal cycled. At that time an attempt was made to transfer the stack compressive load from the exterior follow-up system to the internal fixed-height system and the dielectric barrier deficiency between the stack and the reactant gas manifolds was corrected.

Restart was marked by an average performance loss of 55 mV/cell at 100 ASF and corresponding increases in cell internal resistance values. Cell cross-leakage was low and continued to be low for the remainder of the test (Figure 2-22). It was determined that the stack compressive load was not adequately transferred to the fixed system and the load, therefore, was transferred back to the external follow-up system. This resulted in a performance recovery of 40 mV/cell average for a net loss of 15 mV/cell and the planned test program was resumed.

An additional performance loss of ∿25 mV/100 ASF occurred at 675 hours when the stack was inadvertantly run fuel-starved for 15-20 minutes. This loss was believed due to the formation of nickel oxide at the anode. Following that incident, performance remained very stable for the next 215 hours at which time the ambient pressure phase of the test program was concluded. The stack is in dry storage awaiting testing at elevated operating pressures.

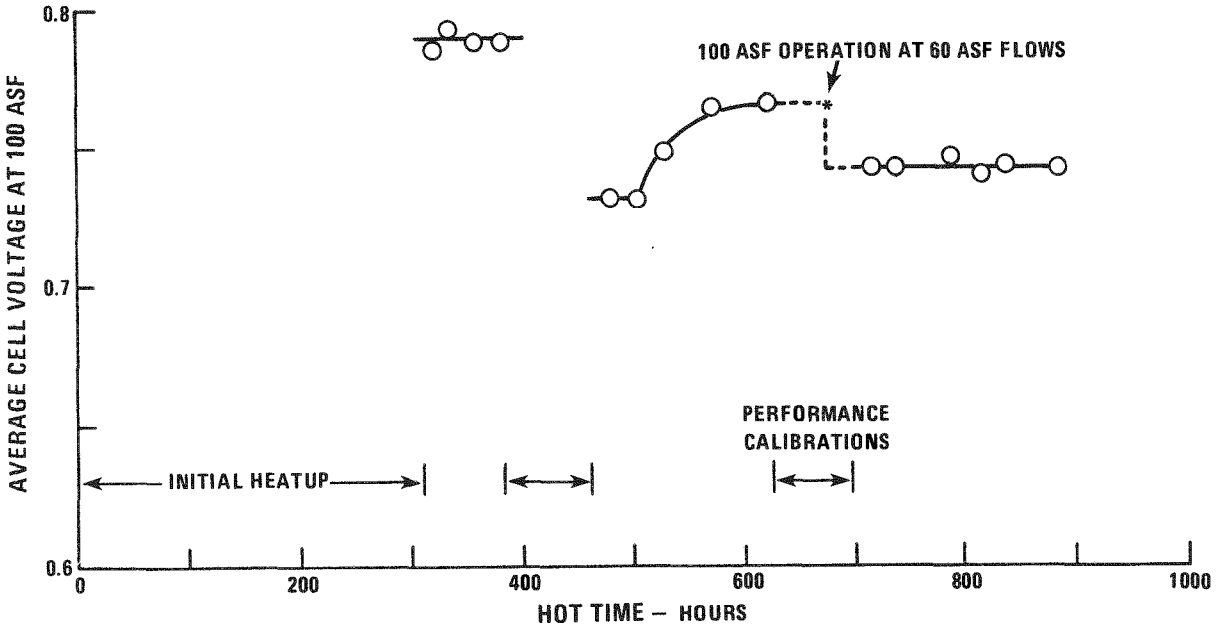


Figure 2-24. 20-Cell Stack Endurance Log
(at conditions given in Table 2-3)

SUBTASK 1.6 - CONDUCT TESTS TO OBTAIN DESIGN DATA ON CARBONATE VAPOR SCRUBBERS

The purpose of this subtask is to evaluate a design approach for scrubbing electrolyte vapors from the stack exhaust streams. The approach taken to obtain design data was to identify potential scrubber materials, screen these materials by exposing them to stack exhaust streams, conduct pressure loss tests on promising materials, and design and test the scrubbers in order to study performance under actual 20-cell stack conditions. The work accomplished during the period of this report included:

- Initial selection of 3 candidate scrubber materials for screening. These materials were:

  --Alumina/silica fibrous blanket.

  --Steel wool.

  --Glass wool.

- Samples of these materials were exposed to the cathode exhaust stream of the rebuilt 16-cell stack tested in Subtask 1.5 for about 650 hours. Post-test examination showed that:

--The glass wool virtually disappeared.

--The steel wool reacted with the carbonate vapors, but became embrittled and crumbled easily.

--The alumina/silica fibrous blanket reacted with the carbonate vapors without suffering any significant structural changes.

- Pressure drop data for designing the scrubbers were obtained on a sample of alumina/silica blanket since it was the most promising candidate.

- Scrubbers were designed and fabricated for the anode and cathode exhaust streams of the Task 1 20-cell stack, capable of pressurized or ambient pressure operation. These scrubber designed are shown in Figure 2-25 and 2-26 respectively.

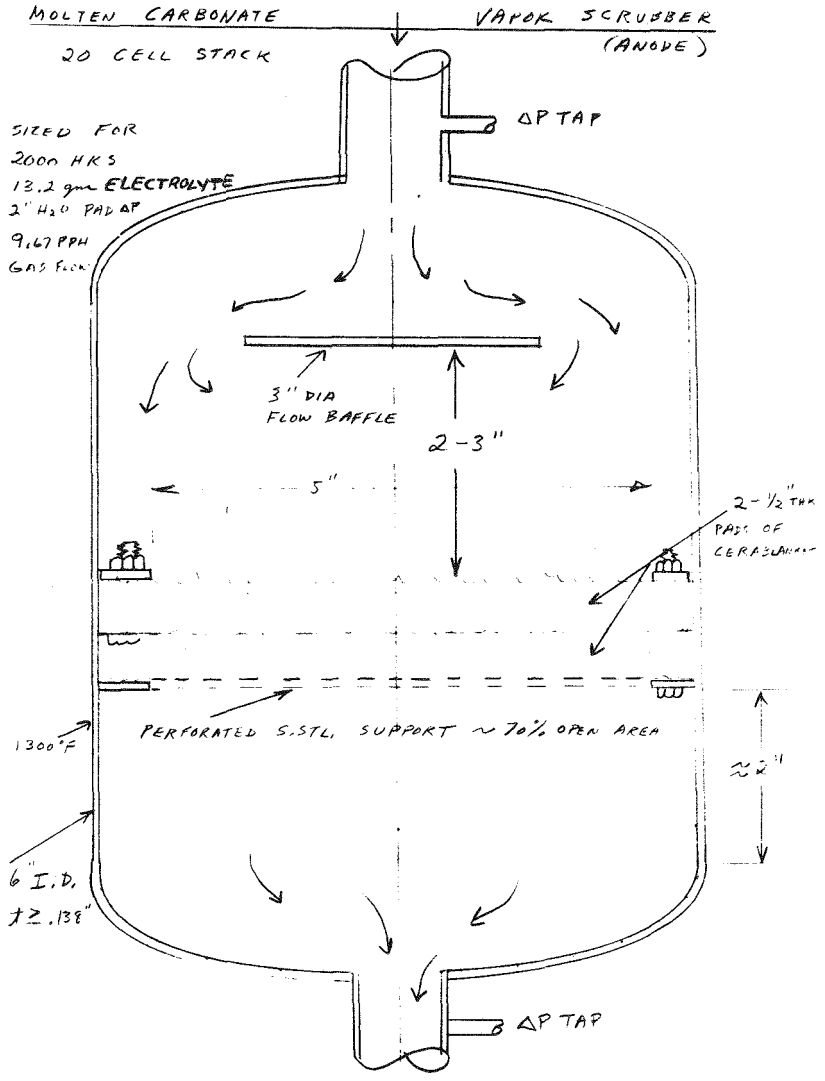


Figure 2-25. Anode Scrubber for 20-Cell Stack

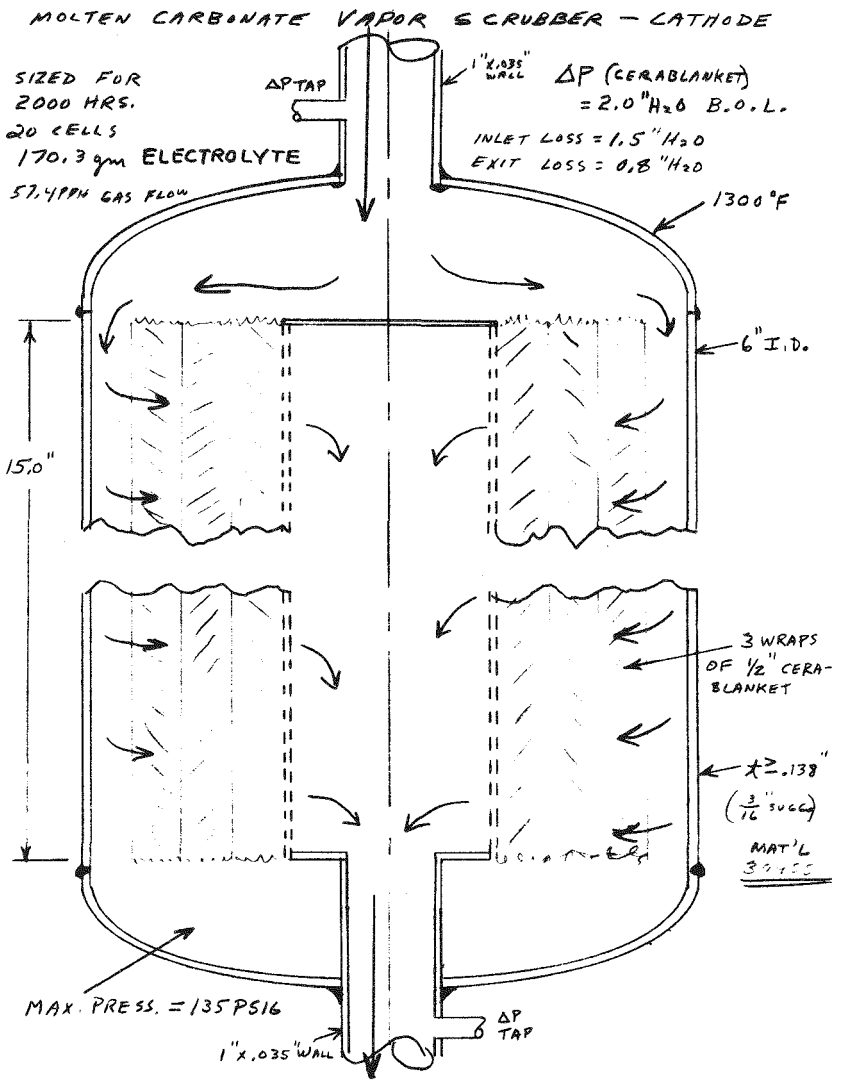


Figure 2-26. Cathode Scrubber for 20-Cell Stack

The 20-cell stack tested in Subtask 1.5 had a pair of scrubbers located in both the cathode and anode exhaust streams as shown in Figure 2-27. The scrubbers in Location No. 1 were small units sized only to test candidate materials and having the exhaust gas flow by, rather than through, the scrubber material. They were designed for low pressure drop and had the gap between specimens sized to promote diffusion of carbonate vapor to the fibers of the scrubber material. These units were adjacent to the exhaust manifolds and were insulated to prevent condensation of carbonate vapors. The scrubbers in Location No. 2 were also designed for low pressure drop, were located outside the containment vessel and were sized to remove all of the carbonate vapors expected from 2000 hours of 20-cell stack

operation assuming that 10 percent of the scrubber material reacted during the test. These are the scrubbers shown in Figure 2-25 and 2-26. The lines connecting the scrubbers were heated to prevent carbonate vapor condensation. The objective of this initial scrubber testing is to:

- Determine the degree of chemical reaction between the carbonate vapor and the candidate scrubber material.
- Determine the degree of carbonate deposition and chemical attack on the exhaust lines.
- Determine scrubber effectiveness by comparing the amount of carbonates trapped in the scrubbers and exhaust lines to the evaporative loss predicted using laboratory vapor pressure data.
- Establish the effects of long term exposure to carbonate vapors on pressure drop and other physical properties of the scrubber materials.
- Determine the ultimate capacity of the scrubber materials for sizing scrubbers for large powerplants.

The scrubbers are scheduled for continued testing with the 20-cell stack at pressure in Subtask 1.5.

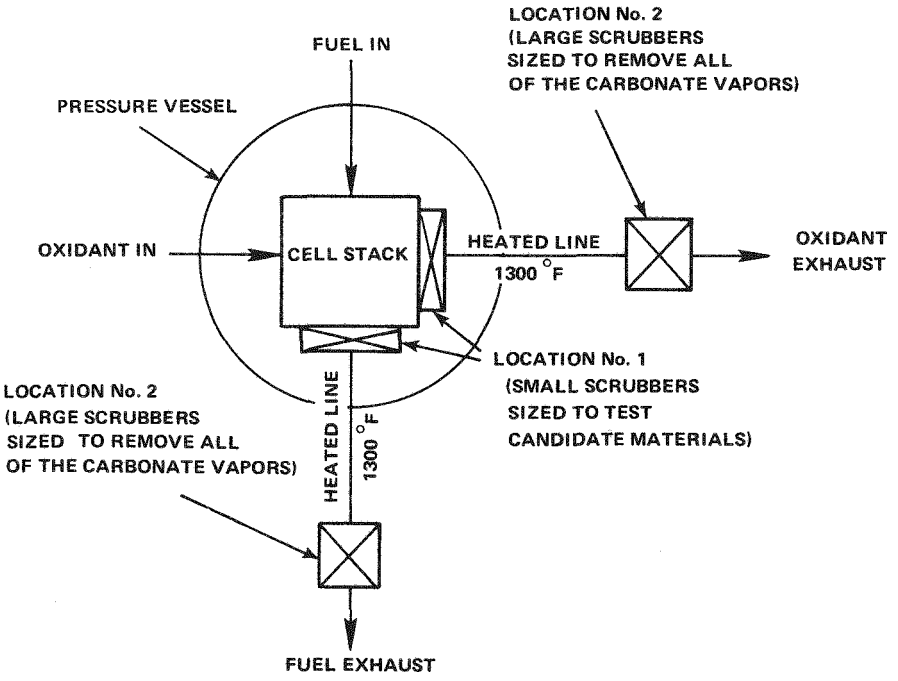


Figure 2-27. Location of Carbonate Vapor Scrubbers

Section 3

TASK 2 PRESSURIZED STACK TEST

OBJECTIVES AND SCHEDULE

The primary objective of Task 2 is to assemble and test a pressurized stack of 20 or more one-square-foot cells for at least 1000 hours to show that the stack is compatible with operation at pressure, that the stack and pressure vessel designs are satisfactory, and that the stack will withstand cross pressures imposed by steady-state and transient system operation. A carbonate vapor scrubber and anode exhaust burner are also to be evaluated as part of this stack test.

The Task 2 activity during this report period is identified in Figure 1-1, giving the corresponding milestone schedule by individual subtask, and showing that work has been initiated on the test stand design in Subtask 2.2 and on the pressurized stack design in Subtask 2.4.

This section describes the work accomplished and the results achieved in Task 2 through the end of December, 1979.

SUBTASK 2.2 - TEST STAND DESIGN

A breadboard system test will be conducted under Task 3 of this program to demonstrate compatible operation of a molten carbonate stack, an advanced fuel processor, and critical ancillary system components. The breadboard system has been patterned after the conceptual design of a 10-MW dispersed power plant conducted under RP114-2 and assumes the use of the advanced fuel processor from RP1041-4. The objective of this subtask is to design the test facility that will be used to test the breadboard system. The design of the power section side of the facility, which will also be used for earlier testing of 20-cell pressurized stacks in Task 1 and 2 of the program, was completed during this report period and construction is now in progress. Figure 3-1 shows the test stand being constructed.

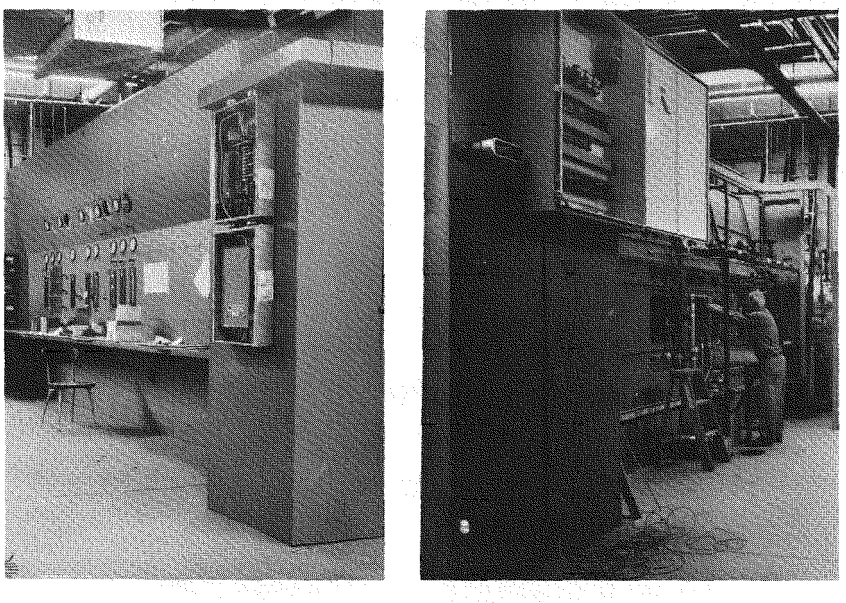


Figure 3-1. Test Stand Under Construction

Engineering studies determined the effect of stack operating conditions on the system flow rates and on the number of cells required to produce 20-kW of power and showed other test interactions between the breadboard components. Stack operating conditions were selected for the purpose of designing the test facility. The results of the study and the breadboard conditions selected are discussed briefly in the following paragraphs.

The flow schematic of the breadboard system was patterned after the conceptual RP114-2 power plant design and is shown in Figure 3-2. Number two fuel oil (or coal derived liquid fuel) is converted to a hydrogen rich gas in an adiabatic reformer. Sulfur is removed by a regenerable metal-oxide scrubber with residual sulfur absorbed by a bed of zinc oxide. Electrolyte vapors are removed from the reactant exhaust streams by scrubbers and process water is recovered by an anode condenser. The anode vent gas is then burned in a catalytic burner and the exhaust mixed with the cathode inlet stream to supply the necesary CO_2 for the cathode. The waste heat from the cell is removed by cathode-gas recycle. As illustrated in the schematic, the test facility will be designed so that either the fuel processor or the power section side of the breadboard can also be run independently.

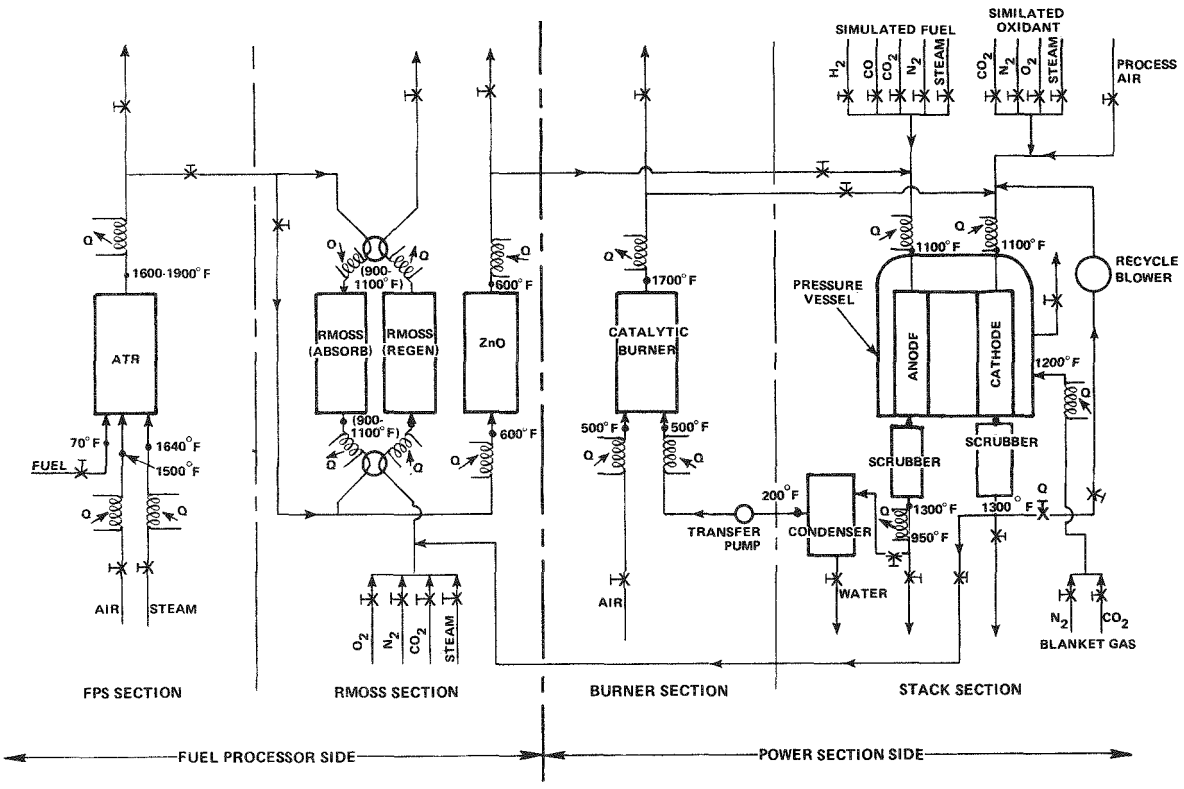


Figure 3-2. 20-kW System Test Schematic

The facility flow requirements were based on the study showing the impact of stack operating conditions on the number of cells and flows required to produce 20-kW of power. The number of cells required decreases with increased stack pressure or with decreased cell operating voltage (increased current) as shown in Figure 3-3 and with decreased fuel utilization as shown in Figure 3-4. The major parameter impacting on fuel processor flows is stack fuel utilization as shown in Figure 3-5. Stack operating pressure has little effect on the flows required and decreased cell operating voltage increases the flow only slightly. If it is necessary to increase the fuel processor O_2/C ratio to 0.5 to avoid carbon formation, one result will be a slight increase in the number of cells required to produce 20-kW of power. The higher O_2/C ratio will also require a 14-percent increase in the adiabatic reformer fuel flow and a 63-percent increase in the air flow.

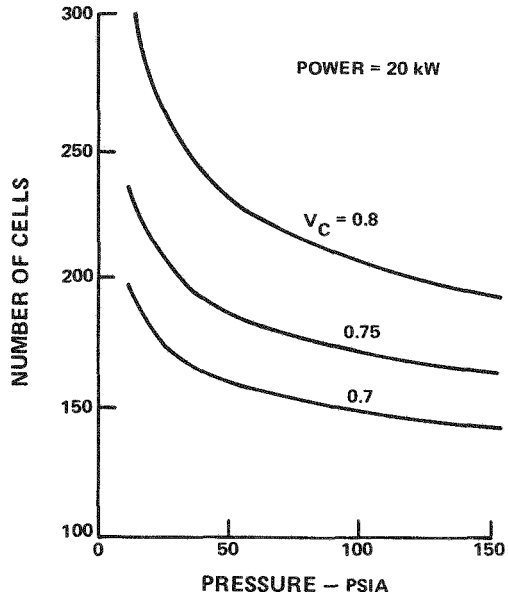


Figure 3-3. Effects of Pressure and Operating Voltage on Numbers of Cells Required

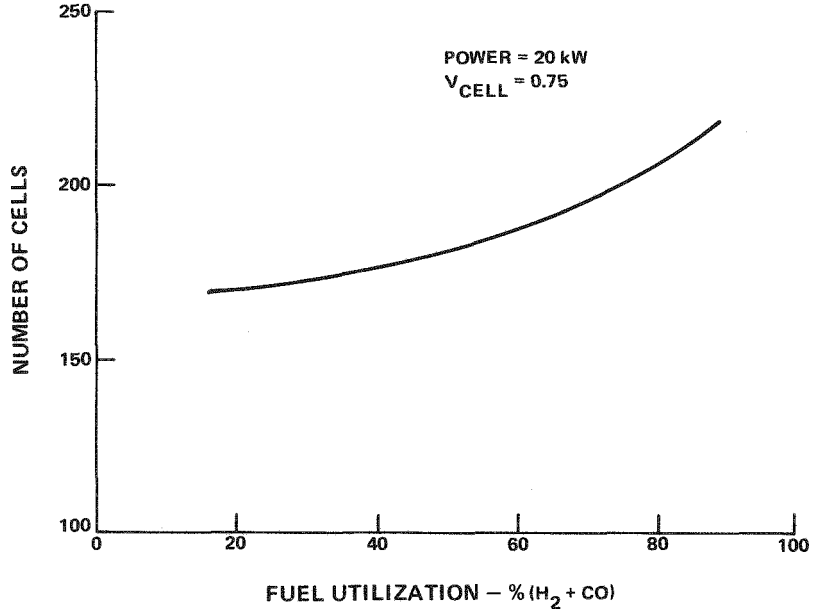


Figure 3-4. Effects of Fuel Utilization on Cells Required

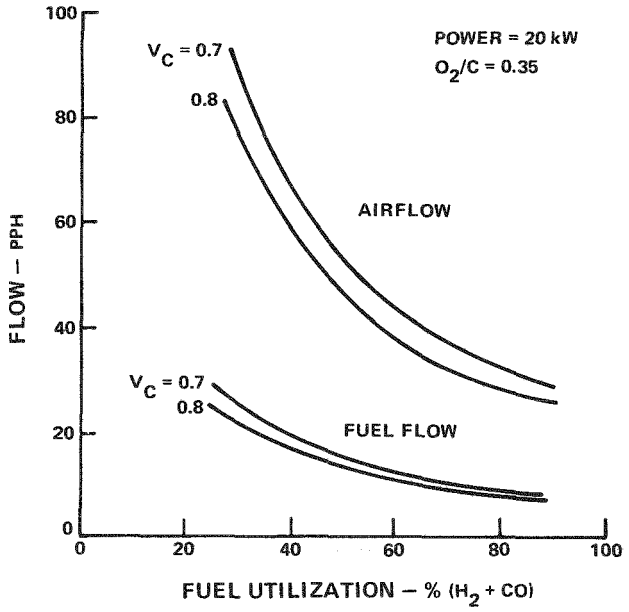


Figure 3-5. Fuel Processor Flows Required

The catalyst intended for use in the anode vent burner sinters and loses activity if operated at temperature above 1600-1700°F. Catalysts under development are expected to raise this temperature limit to 2000-2100°F. This catalytic burner temperature limit restricts the stack fuel utilization as illustrated in Figure 3-6. Decreasing fuel utilization increases the H_2 and CO content in the anode vent, thereby increasing the burner flame temperature. With the design catalytic burner fuel and air preheat temperatures, the stack must always be operated at, or above, 85-percent fuel utilization to prevent damaging the burner catalyst. Since the breadboard system uses stand heaters and coolers rather than integrated heat exchangers to control process temperatures, the catalytic burner preheat temperature could be lowered to 500°F permitting operation with a stack fuel utilization of about 65-percent. If necessary, this could be lowered to 45-percent by not removing water from the anode vent gases.

The breadboard operating conditions selected for designing the test facility are listed in Table 3-1. The fuel utilization of 70-percent was selected to stay within the catalytic burner limits and to keep the adiabatic reformer fuel flow within the nominal range of the 10 pph reactor design from RP1041-4. The 70-percent fuel utilization and a O_2/C ratio of 0.5 were selected so the required reformer flows would be on the high side and the facility would have capacity in excess of 20-kW. The 90 psia operating pressure is a nominal value: the facility will have the capability for operation up to 150 psia. Pressure increases

beyond 90 psia do not change the flow requirements, but would improve cell performance.

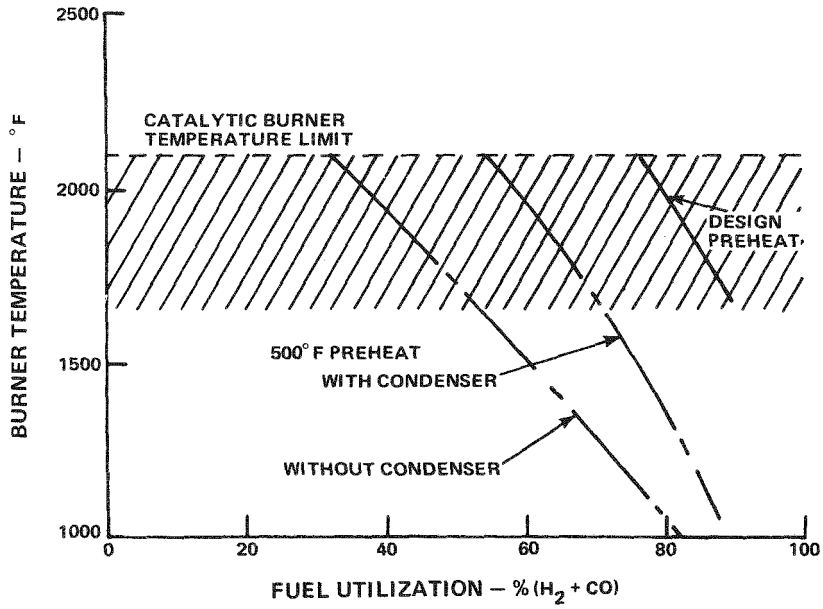


Figure 3-6. Catalytic Burner Limits

Table 3-1.
BREADBOARD OPERATING CONDITIONS

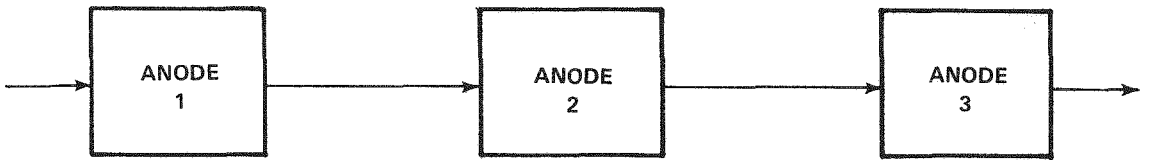
Power	20 kW
Pressure	90 psia
Number of Cells	200
Current Density	177 ASF
Cell Voltage	0.745
(H_2 + CO) Utilization	70%
O_2 Utilization	67%
Stack Airflow	114 pph
ATR Fuel Flow	11.5 pph
O_2/C	0.5
ATR Airflow	57.5 pph
ATR Steam Flow	56.1 pph

The test conditions shown in Table 3-1 resulted from the above trade-off studies to size the major system components for operation in a breadboard mode. Table 3-2 shows the expected gas compositions and flow rates for this breadboard system test. These conditions differ slightly from those of the 10-MW conceptual design because the breadboard stack is a single pass system and other components, such as the adiabatic reformer, are not expected to operate at conceptual design conditions. A line schematic of the anode fuel-flow configuration assumed in the conceptual design is shown in Figure 3-7. This system was chosen to provide high fuel velocities, thereby minimizing stack maldistribution requirements. The fuel compositions and reactant utilizations for each pass of the 3-pass series flow arrangement are also shown. Similarly, the cathode oxidant flow configuration is shown in Figure 3-8 together with the oxidant composition and utilization following recycle. The reactant compositions and utilizations corresponding to the second pass of this design have been selected as base-line operating conditions for future pressurized stack testing in this program.

The baseline gas compositions will be supplied by gas mixing stations. A pressurized gas mixing station was designed and is also presently under construction to provide for the continuous operation of stacks to pressures of 150 psia.

Table 3-2
MOLTEN-CARBONATE BREADBOARD SYSTEMS TEST

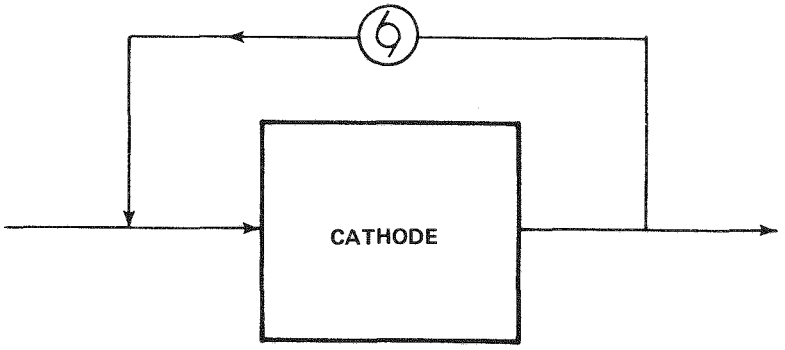
Gas Compositions	Anode In (Dry Vol. %)	Cathode In (Dry Vol. %)
H_2	33.43	--
CO	10.64	--
CO_2	12.54	16.21
O_2	--	8.13
N_2	43.37	75.64
H_2O/Dry Gas (vol/vol)	0.741	0.093
Flow (pph wet)	124.42	601.13
Ave. Molecular wt (wet)	19.07	29.822



Anode Inlet Flows (Vol % Dry)

Gas Conditions	Anode 1	Anode 2	Anode 3
H_2	36.7	26.0	14.2
CO	8.9	5.4	4.2
CH_4	0.2	0.2	0.2
CO_2	22.1	37.4	50.8
N_2	32.0	31.0	30.6
Fuel Utilization (%H_2 + CO)	(29.0)	(40.7)	(68.7)
H_2O Content vol%H_2O/Vol Dry Gas	(.76)	(.83)	(.93)

Figure 3-7. Conceptual Design Fuel Flow Configuration



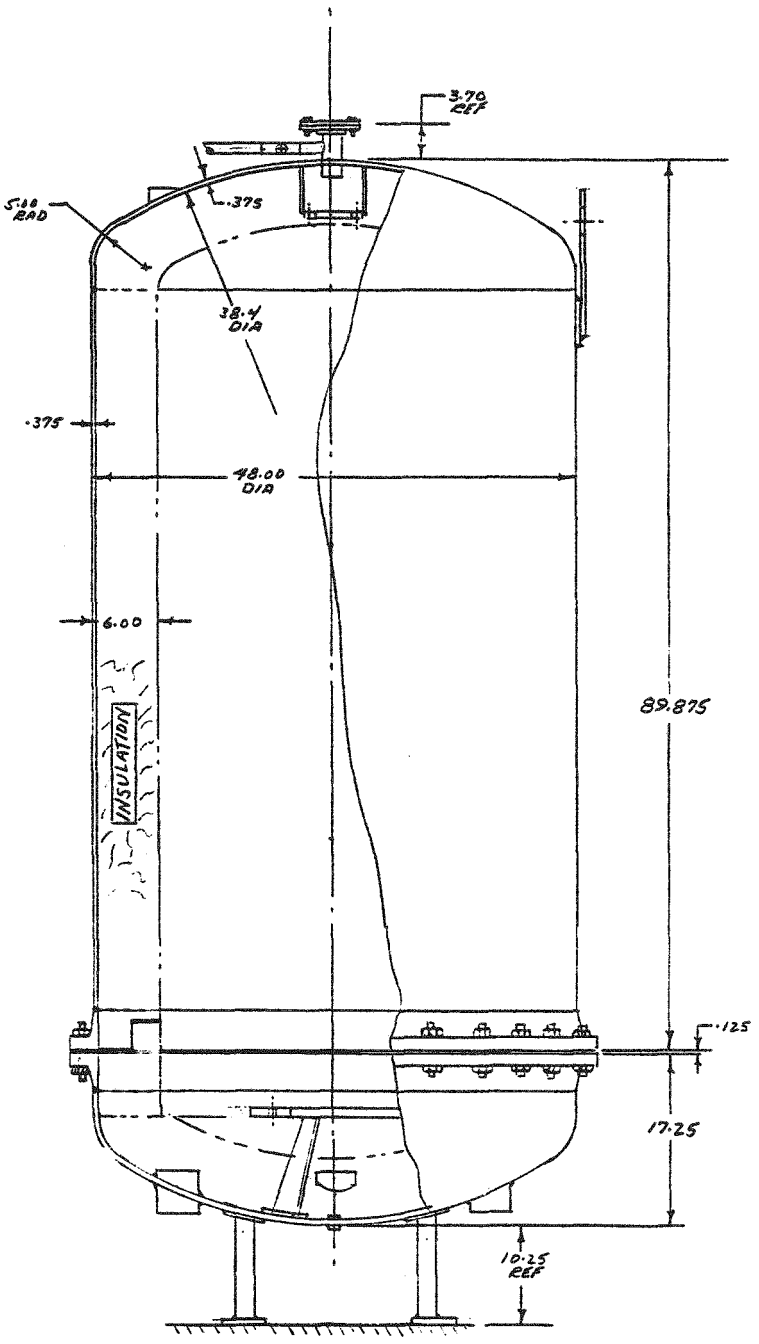
Gas Conditions	Inlet Flow With Recycle (Vol. % Dry)
O_2	8.2
CO_2	16.2
N_2	75.6
O_2 Utilization (%)	(36.8)
CO_2 Utilization (%)	(37.0)
H_2O Content Vol H_2O/Vol Dry Gas	(.093)

Figure 3-8. Conceptual Design Oxidant Flow Configuration

SUBTASK 2.4 - PRESSURIZED STACK DESIGN

The objective of this subtask is to continue the stack design work initiated in Subtask 1.2 through to completion of the construction drawings and component specifications for the 20-kW stack to be assembled and tested in Task 3. This effort integrates into the stack design the progress of parallel programs which are continuing the development of component processes and cell configurations. A 20-cell assembly of this pressurized stack design is to be tested for initial verification in Task 2. The work during this report period concentrated on the design of the pressure vessel to be used to satisfy testing in both Tasks.

The design layout of a containment vessel to house a stack of up to 200 cells of one-square-foot size for high pressure operation has been completed. Figure 3-9 shows this design layout. A layer of thermal insulation on the inside diameter of the vessel is included to keep the wall temperature below 500°F. Stack planform dimensions and insulation thickness require a vessel of 48-inch diameter by 107-inches high to insure ample room for access during the test program. The design pressure is 150 psia. All component parts have been designed to meet the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. The materials used in the vessel are: 0.375-inch thick SA515 GR70 carbon steel for cylinder and heads, SA105 carbon steel for the flanges, and SA193 GR7B for flange bolts. The flanges are designed to use an asbestos gasket while the heads selected are ASME 80/10 torispherical shape to reduce die cost. This vessel is presently on order.



CONTAINMENT VESSEL FOR

200 CELL STACK ASSY

Figure 3-9. Pressure Vessel Design Layout

Section 4

TASK 3 SYSTEM TEST OF 20-kW STACK WITH ADVANCED REFORMER

OBJECTIVES AND SCHEDULE

The primary objective of Task 3 is to fabricate and test a nominal 20-kW system comprising a pressurized adiabatic reformer and clean-up system, a pressurized stack of more than 100-cells, and critical system components for approximately 1000 hours in a breadboard system mode in order to confirm that the cell-stack operates properly on reform/clean-up gases, that no fuel gas carbon is formed, that anode gas chemical kinetics are understood, that major heat exchangers operate satisfactory, and that carbonate vapors are adequately scrubbed.

The work breakdown structure of Task 3 is shown in Figure 1-1 listing the individual subtasks. No work was scheduled or performed in Task 3 during the period of this report.

Section 5

REFERENCES

1. "Advanced Technology Fuel Cell Program", Project RP114-2 Annual Report No. EM-1328, January 1980, Power Systems Division of United Technologies Corporation.

2. "Advanced Technology Fuel Cell Program", Project RP114-2 Annual Report No. EM-956, December 1978, Power Systems Division of United Technologies Corporation.

3. "Cogeneration Technology Alternatives Study (CTAS)", Final Report, six volumes, Nos. NASA CR 159759 through 159764, January 1980, Power Systems Division of United Technologies Corporation.

4. "Advanced Technology Fuel Cell Program", Project RP114-1 Final Report No. EM-335, October 1976, Power Systems Division of United Technologies Corporation.

5. "Advanced Technology Fuel Cell Program", Project RP114-2 Interim Report No. EM-576, November 1977, Power Systems Division of United Technologies Corporation.

6. NASA CR 134955, "Energy Conversion Alternatives Study", United Technologies Phase II Final Report, Integrated Coal Gasifier/Molten Carbonate Fuel Cell Power Plant Conceptual Design and Implementation Assessment, October 16, 1976.

7. "An Engineering Study of Fuel Cell and Gas Turbine Combined Cycles" Project RP239-4, Report No. AP1543 Fluor Engineers and Constructors

8. "Development of Molten-Carbonate Fuel Cell Power Plant Technology", Quarterly Technical Progress Report No. DOE/ET/15440-1, March 1980, Power Systems Division of United Technologies Corporation.

9. "Advanced Technology Fuel Cell Program", Project RP114-2 Final Report forthcoming, Power Systems Division of United Technologies Corporation.