FOSSIL

DOE/ET/17089-2854
(DE90009665)

Design, Fabrication and Testing of a Solid Oxide Fuel Cell Stack for a 25 kW to 200 kW Generator

Annual Report
March 1986 - March 1987

May 1987

Work Performed Under Contract No.: DE-AC21-80ET17089

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Westinghouse Electric Corporation
R&D Center
Pittsburgh, Pennsylvania

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615)576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

Price: Printed Copy A04
Microfiche A01

Printed in the United States of America. Office of Scientific and Technical Information, Oak Ridge, Tennessee

DOE/ET/17089--2854

DE90 009665

Design, Fabrication and Testing of a Solid Oxide Fuel Cell Stack for a 25 kW to 200 kW Generator

Annual Report
March 1986 - March 1987

Work Performed Under Contract No.: DE-AC21-80ET17089

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

By
Westinghouse Electric Corporation
R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

May 1987

ABSTRACT

The objective of the High Temperature Solid Oxide Electrolyte Fuel Cell Power Generation System project is to perform research and development on fuel cells, modules and systems, which are requisite to the commercialization of the technology. The commercial systems are envisaged to encompass a range of ratings from a few hundred kilowatts to scores (and possibly hundreds) of megawatts, with applications from total energy systems for commercial buildings to electric power units operating on coal derived gas.

The effort reported herein was carried out over the period from March 1986 through March 1987, the first year of a three year contract modification (A030) to Contract DE-AC21-17089 (prior number: DE-AC02-17089), The High Temperature Solid Oxide Electrolyte Fuel Cell Power Generation System. Prior effort under the contract covered the period since June 1980 and culminated in placing on test a 5 kilowatt (kW) generator. Intermediate steps included testing of many materials and single cells (~15 watts), a three cell bundle (~45 watts) that was operated successfully for 9000 hours, and a 24 cell (~400 watt) submodule that was operated successfully for more than 2000 hours.

The solid oxide fuel cell (SOFC) concept, on which this program was based, operates on a well demonstrated principal of oxygen ion transport driven by the differential pressure of oxygen across the cell. The cell is composed of five components: 1) a porous tube of calcia stabilized zirconia, 1.27 centimeters in diameter, two millimeters in thickness, closed at one end, that serves as the structural element; 2) a one millimeter layer of lanthanum manganite that provides the air (positive) electrode; 3) a solid electrolyte (oxygen ion conductor) layer of yttria doped zirconia that covers some 280 degrees of the circumference of the tube; 4) an interconnection layer, covering the

remaining 80 degrees, composed of lanthanum chromite, provides an electrical connection from the positive electrode of one cell to the negative electrode of the adjacent cell or to the power take-off, and along with the electrolyte completes the gas barrier; and 5) a nickel cermet fuel (negative) electrode that covers some 265 degrees of the circumference. The active length of the cells developed in this program is about 30 centimeters. Oxygen is provided to the process by feeding air into the cell through an inner (smaller) alumina tube. This tube extends down into the vertical fuel cell from an air manifold at the top of the module. Fuel is furnished to the outside of the cell, from the bottom. In this manner, the oxygen and fuel both flow along the cell wall in the same upward direction and their depletion in the electrochemical process is properly matched.

The technical effort in the current modification is organized under three technical tasks that have objectives as follows:

1. To define a reference design, subsystem design, and component requirements for a tubular solid oxide fuel cell plant with the greatest potential to be commercialized,

2. To develop and verify cell performance, which satisfies the component requirements, and

3. To develop and verify stack performance, which satisfies the component requirements.

In addition, post test analyses of the 5 kW generator have continued during this reporting period. A total of 360 cells were operated in the two tests of the 5 kW generator. These, along with components of the module, provide operating results from a wide range of in-module conditions.

TABLE OF CONTENTS

		Page
1.0	BACKGROUND	1
2.0	PROJECT SCOPE	7
3.0	WBS 9.0 -- ESTABLISH REFERENCE DESIGN	9
4.0	WBS 10.0 -- IMPROVE AND VERIFY CELL PERFORMANCE	33
5.0	WBS 11.0 -- DEVELOP AND VERIFY STACK PERFORMANCE	53
6.0	SUMMARY PLAN FOR THE NEXT PERIOD	59

LIST OF FIGURES

		Page
1-1	A Practical Solid Oxide Fuel Cell Configuration, with Fuel on the Outside	3
1-2	Completed Bundle of Cells Showing Series/Parallel Configuration	4
1-3	Seal-less Generator Concept	5
3-1	IG/SOFC Simplified Block Schematic	17
3-2	Flow Schematic of SOFC Systems Model for Fluidized Bed Coal Gasifier Subsystems with External Desulfurization	18
3-3	Modular IG/SOFC Power Plant Gas Cleanup/SOFC Flow Diagram	19
3-4	Modular IG/SOFC Power Plant Gas Cleanup/SOFC Flow Diagram	20
3-5	Comparison of Coal Gasifiers for SOFC - Power Systems Applications	21
3-6	Plant Heat Rate vs Fuel Utilization for IG/SOFC (1 atm/600 mV) 200 MW Plant	23
3-7	Effect of Fuel Utilization SOFC Gas Temperature (10 atm)	24
3-8	SOFC Enclosure Costs vs Module Size	25
3-9	Baseline Cell Configurations	26
3-10	V-I Curves for Different Fuel Cell Designs	27
3-11	Layout of SOFC Modules Illustrating Integrated Building Block Arrangement	28
3-12	IG/Atm SOFC Cost of Electricity - Cell Voltage Parametrics	29
4-1	End View of Disassembled 5 kW Generator	34

4-2 Cell Stress Characteristic Observed During Manufacturing 41

4-3 Fuel Electrode Shrinkage vs Sintering Temperature for Various Dopants 45

5-1 Voltage vs Time Curve for Test Cell #114 56

LIST OF TABLES

		Page
3-1	Candidate Users/Applications for Large-Scale SOFC Power Plants	11
3-2	IG/SOFC Plant Design Requirements	14
3-3	Coal Gasifier Models for SOFC Systems Analysis	15
3-4	Summary of SOFC System Performance	16
3-5	Basis of Commercial Scale SOFC Generator Conceptual Design and Cost	30
3-6	Design Requirements for Truck Transportable SOFC Module	31
3-7	Cell Reliability and Module Design	32
4-1	Cells Selected, from the 5 kW Stack, for Destructive Examination	38
4-2	Cells Tested at Temperature. Results are Presented in Table 4-3	50
4-3	Cells Testing Summary. Major Experimental Variables are Presented in Table 4-2	51

1.0 BACKGROUND

Prior work, supported partially by Government agencies and partially by Westinghouse, had demonstrated the feasibility of direct conversion of fuel energy to electric energy with the solid oxide method.

The solid oxide fuel cell (SOFC) operates at temperatures in the range of 1000°C (1800°F) providing reject heat at temperatures that are attractive for process heat applications or production of additional electric power in a bottoming cycle. Very high efficiency can be achieved over a range from very small to large unit sizes.

The cell is capable of operation on hydrogen (H_2), carbon monoxide (CO), and potentially on methane fuels, which means that coal derived and/or natural gases may be used with a minimum of fuel processing.

The SOFC systems will be environmentally benign. All energy in the fuel is converted to electric energy or heat at 1000°C, a temperature at which the production of oxides of nitrogen (NO_x) is negligible.

Many solid oxide fuel cells had been produced and tested at Westinghouse. These were of a configuration that placed the fuel inside the cell and air on the outside. These were adequate for the demonstration of the feasibility of the basic cell but were not easily adapted into multi-cell bundles, e.g., the cell to cell electrical connection would have to be completed on the air side and practical electrical conducting materials with long life in air at 1000°C do not exist.

The solid oxide fuel cell with fuel on the outside (Figure 1-1), series/parallel bundles of cells (Figure 1-2) and the seal-less generator (Figure 1-3) concepts were conceived by Dr. Isenberg of the Westinghouse R&D Center. These represented the breakthrough that was needed to proceed with the development of a practical SOFC configuration and they were incorporated as the basis for this effort.

In addition to many individual cell tests, 3-cell and 24-cell devices have been tested for thousands of hours.

The prior phase of the program culminated in the test of a 5 kW generator, consisting of 324 cells (Figure 1-4). This test device was operated at outputs as high as 5.3 kW in two separate test cycles. Analyses suggest that an output of 6 kW might have been obtained, proving another step in the scale-up methodology. The operating results indicate problems must be solved in the course of achieving practical lifetimes for the cell and module. These problems are being explored in post test analyses aimed at delineating the causes and directions for their resolution.

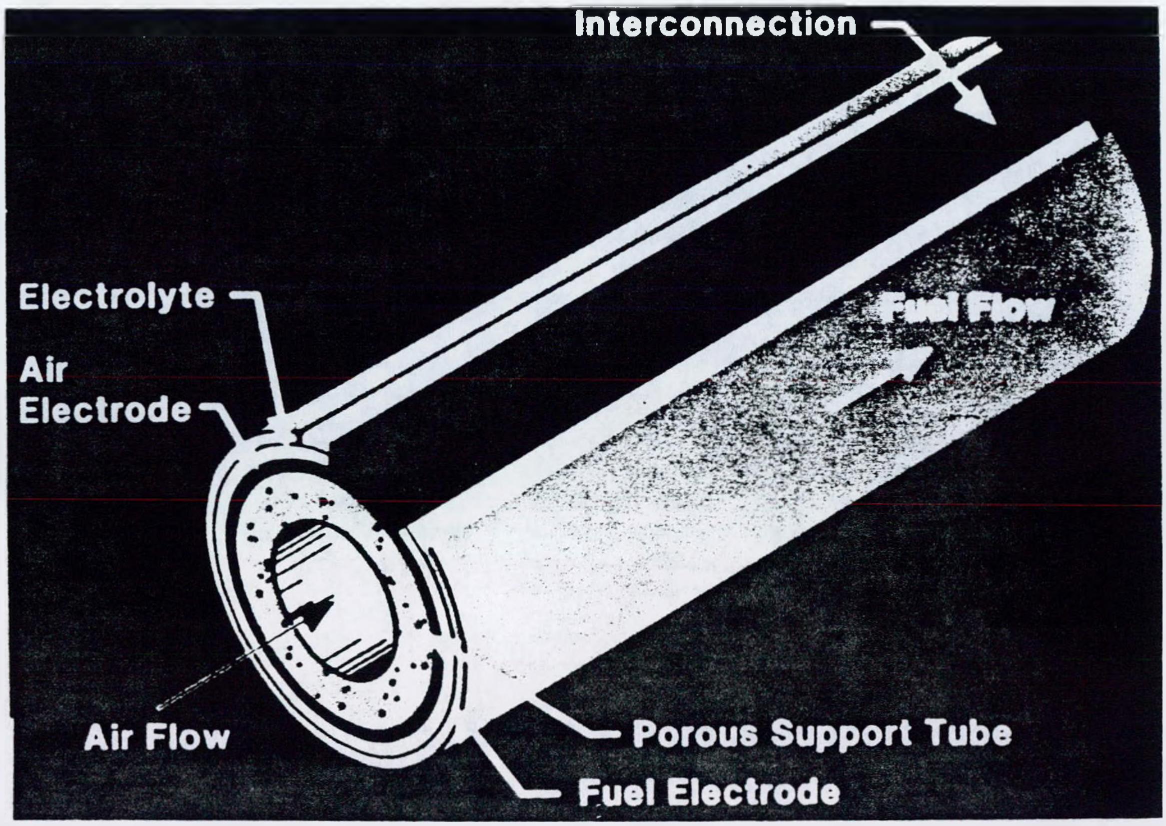


Figure 1-1 — A Practical Solid Oxide Fuel Cell Configuration, with Fuel on the Outside.

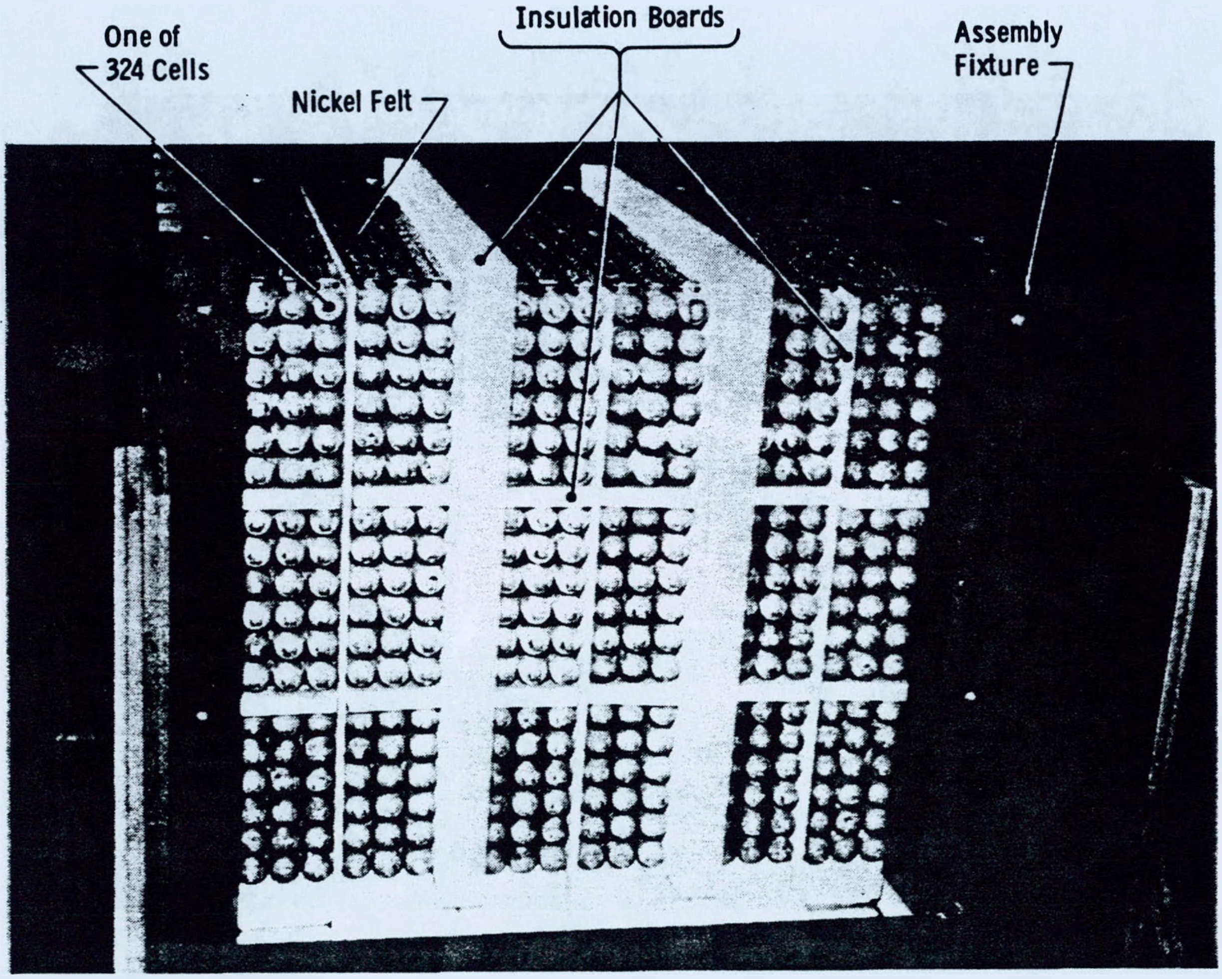


Figure 1-2 — Completed Bundle of Cells Showing Series/Parallel Configuration.

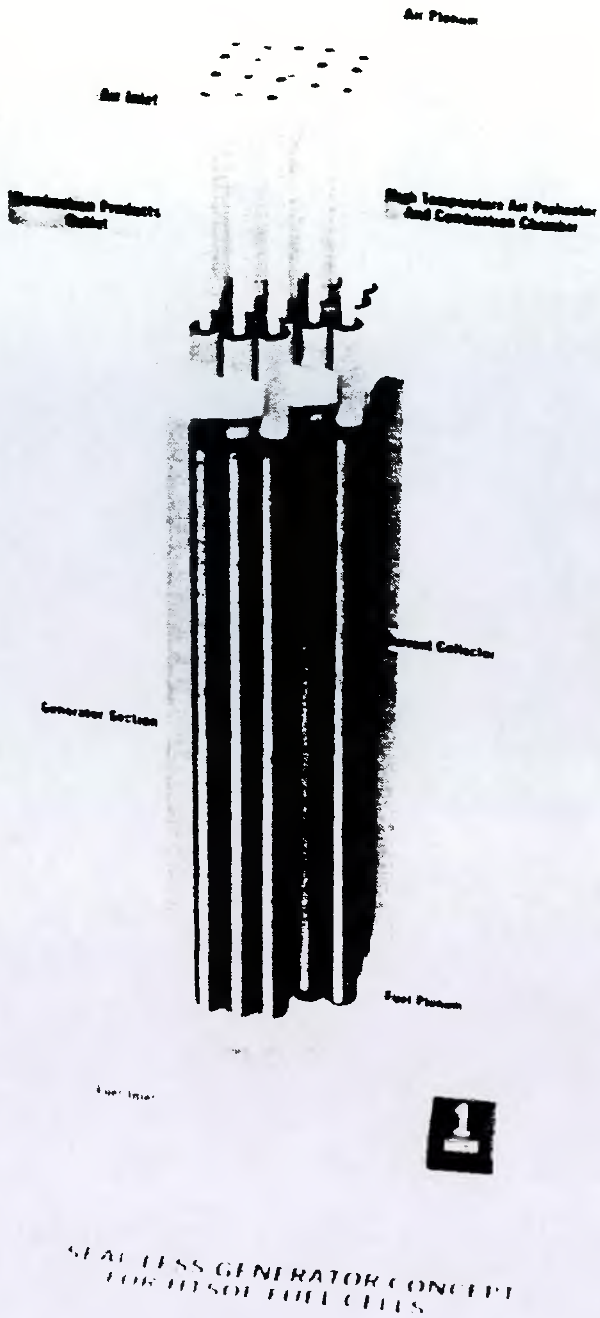


Figure 1-3 — Seal-less Generator Concept.

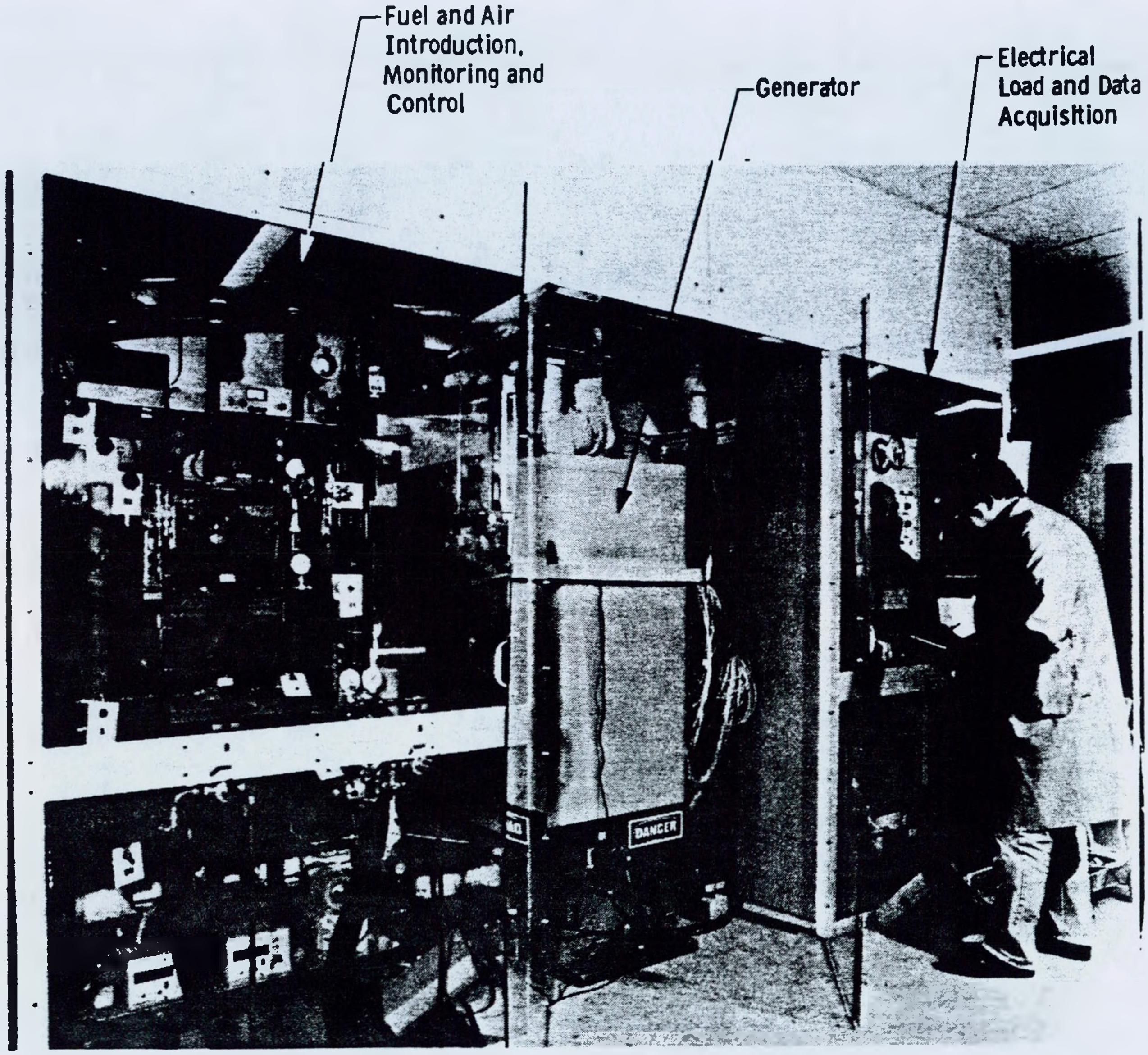


Figure 1-4 — 5 kW Solid Oxide Fuel Cell Generator (Center), Shown in Test Facility.

2.0 PROJECT SCOPE

The current phase (this reporting period plus two additional years) is intended to achieve the design, development and test of a multi-kW generator in early 1989. Improved cell and stack technology is to be developed and incorporated into the multi-kW design. Lessons learned from the 5 kW test are to be applied. Engineering studies of the long range potential of the solid oxide fuel cell are to be conducted, based on technical and economic requirements established with candidate user personnel. One product of these studies is to be definitized design and development requirements, which are intended to provide guidance for the cell and stack development tasks. The current contract scope includes:

1. Establish reference design, including user requirements, conceptual designs and component design requirements.

2. Improve and verify cell performance, including cell fabrication, development of cell components and cell testing.

3. Develop and verify stack performance, including stack fabrication, development of module hardware and stack testing.

3.0 WBS 9.0 -- ESTABLISH REFERENCE DESIGN

This task, Task 1 of the work scope, is intended to provide direction for the improvement and verification of cell and stack technology that is to be carried out under Tasks 2 and 3. The System Engineering Approach (top-down engineering) methodology is to be applied. The first step is to work with user organizations to establish functional requirements and goals for the early market entry (25 to 200 kW, natural gas fueled) and the mature market plants (greater than 20 MW, coal-derived gas fueled). The conceptual design effort will then be guided by these requirements and goals. The component design requirements will be derived from the results of the conceptual design efforts. The final step will be the detailed design of the cell and stack for the unit to be fabricated and tested under this phase of the program.

This task is divided into four subtasks reflecting the above noted four steps: 1.1 Establish User Requirements, 1.2 Establish and Optimize Conceptual Design, 1.3 Establish Component Design Requirements, and 1.4 Establish Detailed Design. These are discussed in the following subsections 3.1 through 3.4.

3.1 ESTABLISH USER REQUIREMENTS

The major portion of the effort which has been completed has been applied to the investigation of the mature market units for electric power and large cogeneration application. This decision was taken with the thought in mind that the first order of business was to delineate the ultimate technical and economic requirements of mature commercial units. Having accomplished this, it will be practical to consider the early market entry units in terms of selections and designs that form a logical technical progression from the present state of the art to the ultimate cell and stack.

Nine candidate cases, see Table 3-1, were identified for integrated gasifier/solid oxide fuel cell (IG/SOFC) plants and natural gas plant studies of users/applications. The requirements, pertinent to these applications, were listed and assigned preliminary values.

A number of electric utility organizations were invited to participate in the project by providing review and assessment of the candidate applications and the user requirements. Six utilities have been active in this effort to date. Response has also been received from EPRI. Other organizations have been invited and are considering participating in the project. A similar advisory council, that would include gas utilities, is anticipated in connection with the effort on the early market entry unit studies.

The applications having, based on the utilities review, the most promise of meeting utility needs in the 1990's were: 1) central station IG/SOFC, 250 - 500 MWe, fueled with coal and operated as a baseload plant, 2) re-powering of existing plants, 150 - 300 MWe, may be fueled with coal, oil or gas and 3) modular dispersed SOFC, 5 - 50 MWe, may be fueled with coal gas or natural gas. Accordingly, the central station application was chosen for use in conceptual design - at a capacity level of 250 MWe. This reflects the predominant utility view that central station capacities low in the 250-500 range are preferred. In addition, the utility review also produced several specific comments relative to baseload plant operation:

The target availability for baseload plants should be 85 per cent.

Baseload plant load change rate of 5 %/min is desirable.

Base and intermediate load plants should exhibit cold startup times of less than 24 hours.

Table 3-1 — Candidate Users/Applications for Large-Scale SOFC Power Plants.

Application No. 1 — Central Station Integrated Gasification/SOFC Power Plant

- Nominal Capacity = 250-500 MW_e
- Base Load, All-electric Design
- Pressurized Coal Gasification System
- High integrated - topping and bottoming cycles, integrated heat recovery, etc.
- Field-erected

Application No. 2 — Modular Integrated Gasification/SOFC Power Plant

- Nominal Capacity = 20-50 MW_e
- Intermediate Load, All-electric Design
- Pressurized or Atmospheric Gasification
- Some Thermal Integration
- Modular Design; Minimal Site Construction
- Load Following Capability
- Good Part Load Heat Rate

Application No. 3 -- Large Industrial Cogeneration Power Plant

- Nominal Capacity = 20-50 MW_e (30-150 MW_t)
- Cogeneration of Electricity and Process Steam
- Electric/Thermal Ratio = 0.3-2.0
- Modular Design; Minimal Site Construction

Application No. 4 — Dispersed SOFC Power Plant

- Nominal Capacity = 5-50 MW_e
- Pipeline Gas (Natural Gas or Coal Gas)
- Insitu Reforming for High Methane Gas
- Cogeneration of Process Heat and Electricity
- Load Following Capability
- Modular, Expandable Design
- Good Part Load Efficiency
- Minimal Environmental Impact

Table 3-1 — Candidate Users/Applications for Large-Scale SOFC Power Plants. (Cont'd)

Application No. 5 — Repowering of Existing Oil or Gas-fired Power Plant

- Nominal Capacity = 50-200 MW_e
- Replacement of Boiler System with SOFC Plus Heat Recovery
- Intermediate Load, All-electric Design
- Modular, Compact, Short Lead-time Design

Application No. 6 — Repowering of Existing Coal-fired Power Plant

- Nominal Capacity = 100-300 MW_e
- Retrofit Coal Gasification System
- Integrate SOFC/Heat Recovery with Existing Turbine/Generator
- Base Load, All-electric Design

Application No. 7 — Chlor-alkali Plant

- Nominal Capacity = 20-300 MW_e
- Fuel = Byproduct Hydrogen (50%) and Pipeline Gas (50%)
- Cogeneration of DC Power and Steam
- Required E/T Ratio = 1.5 (diaphragm)
- = 3.9 (membrane)
- Base Load Operation

Application No. 8 — Primary Metal Processing Plant

- Nominal Capacity = 50-100 MW_e
- IG/SOFC or Pipeline Gas-fueled
- Cogeneration of Electricity and High Temperature (1000-3000°F) Process Heat
- Base Load Operation

Application No. 9 — Petroleum Refinery

- Nominal Capacity = 50-100 MW_e
- Steam Reforming of Light Hydrocarbon Gases or IG/SOFC
- Cogeneration of Electricity and Process Steam
- Some Load Following Required

A baseload plant should operate with less than 10 people/shift.

SOFC module lifetime should be greater than 5 years.

Plot plan area should not exceed that for integrated gasifier combined cycle and be no greater than the 10 MW/acre used for phosphoric acid fuel cell plants.

Therefore, the design requirements for the integrated gasifier solid oxide fuel cell plant study were modified as shown in Table 3-2.

3.2 ESTABLISH AND OPTIMIZE CONCEPTUAL DESIGN

The simplified block schematic of the total IG/SOFC plant is shown in Figure 3-1. The objective of the solid oxide fuel cell program is to provide an efficient power conversion system that is readily combined with any coal gasification plant. To this end, representative gasification systems have been identified and incorporated into the plant model; see Table 3-3. It is recognized that the interface equipment (e.g., gas cleanup and/or pressure reduction) may be gasifier specific. The fluidized bed gasifier model is shown in Figure 3-2. The SOFC models for unpressurized and pressurized SOFC operation are presented in Figures 3-3 and 3-4, respectively.

The SOFC system has the potential for very low coal to busbar heat rates, under 7300 BTU/Kwh in IG/SOFC plants of reasonable size and ~6800 BTU/Kwh in the case of the pressurized arrangement. Preliminary system analysis results are presented in Table 3-4 and Figure 3-5.

Table 3-2 — IG/SOFC Plant Design Requirements.

Top-Level	
Application	Central Station
Coal Type	All Ranks/High S/High Ash
Capacity MWe	250
Duty Cycle	Base Load
Performance	
Electric/Thermal Ratio	All Electric
Heat Rate, Btu/kWh	<8000
Overall Efficiency (LHV), %	>45
Power Type/Quality	13.8 kV Utility AC
Thermal Type/Quality	None
Availability/Reliability	
Scheduled Outage Rate, weeks	4
Forced Outage Rate, %	<10
Design Availability, %	>85
Capacity Factor, %	70
Operational	
Plant Operation/Control	Distributed Microprocessor (except coal analysis)
No. of Operators per Shift	<15 (<10 desired)
Load Change Response, %/min	5
Cold Startup Time, hours	<48 (<24 desired)
Warm Startup Time, hours	6
Turndown Capability, max/min	4:1
Physical	
Design Lifetime, years	
• Plant Lifetime	30
• SOFC Modules	5
• Coal Gasifier	30
Cyclic Capacity (over design lifetime)	
• Cold Cycles	50
• Warm Cycles	100
Plot Plan Area (incl. coal storage), acres	Site Dependent (no greater than IGCC plants)
Max. Height Above Grade, ft	Unlimited
Environmental	
Gaseous Emissions, lbs/10^6 Btu	
• Sulfur (as SO_2)	.01
• Nitrogen Oxides (as NO_x)	.01
• Particulates	Negligible
• Unburned Hydrocarbons	Negligible
Liquid Wastes, gal/kWh	Zero Discharge
Solid Wastes	Non-hazardous
Water Use, gpm/MW	1.0
Noise level, dBA at Site Boundary	55
General	
Project Lead Time	
• Licensing and Design, years	4
• Construction Time, years	3
Design Type	Field-erected

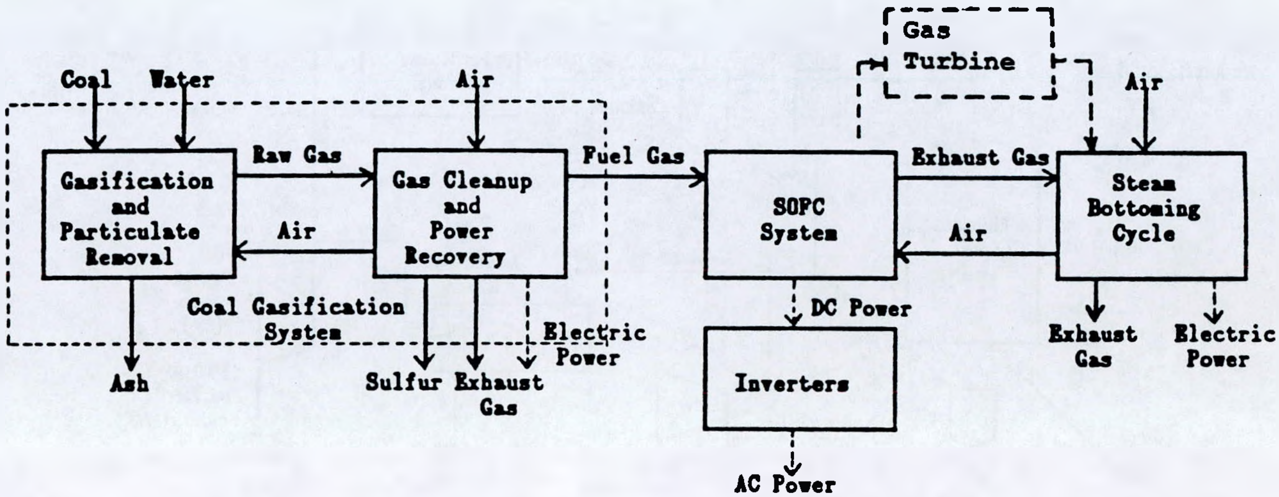
Table 3-3 — Coal Gasifier Models for SOFC Systems Analysis.

Design Parameter	Fluidised Bed KRW-Air Blown External Desulfurisation	Fluidised Bed KRW-Air Blown Insitu Desulfurisation	Fixed Bed LURGI-Air Blown External Desulfurisation	Entrained Bed Texaco-O_2 External Desulfurisation
Coal Type	Illinois #6	Illinois #6	Illinois #6	Illinois #6
Oxident	Air (500°F)	Air (500°F)	Air (500°F)	O_2 (275°F)
Oxident/Coal	3.49	3.31	2.22	0.844
Steam/Coal	0.258	0.251	1.42	NA
Recycle Gas/ Product Gas	0.152	0.184	NA	NA
Carbon Conversion	98.4%	97.6%	93%	99.4%
Cold Gas Efficiency	0.775	0.762	0.814	0.797
Auxiliary Power Req. (kW/TPD)	2.5	1.9	3.5	14.7-15.9
Fuel Gas Pressure	330 psia	330 psia	330 psia	330 psia
Fuel Gas Temp.	1850°F	1850°F	950°F	2300°F
Composition (Mole %)				
CH_4	1.5	3.8	2.9	0.3
CO_2	5.2	7.4	9.7	10.2
CO	20.2	18.3	11.9	40.9
H_2	12.4	9.2	17.2	29.8
N_2	47.7	48.4	29.9	0.8
H_2S	0.5	--	0.5	0.9
H_2O	12.5	12.9	27.9	17.1
MW: lb/lb Mole	24.2	25.0	22.0	20.2

Table 3-4 — Summary of SOFC System Performance.

Power Output (MW)	Atmospheric SOFC KRW/Air/HGC* 50 MW	200 MW	Pressurized SOFC KRW/Air/HGC 50 MW	350 MW
• SOFC - AC	31.6	110.6	34.7	147.2
• Gas Turbine/Generator	--	--	13.7	114.5
• Fuel Expander/Gen.	8.5	29.6	4.7	28.0
• Steam Turbine/Gen.	17.2	66.1	7.8	73.9
Gross AC Power (MW)	57.3	206.3	60.9	363.6
Auxiliary Power (MW)	3.6	8.9	1.9	7.0
Net Power (MW)	53.6	197.4	60.3	356.6
Coal Feed Rate (TPD)	480	1680	480	2880
Net Plant Heat Rate (BTU)/kWH)	7664	7288	6965	6809
Plant Efficiency (%)	44.5	46.8	49.0	50.1

* A Kellog-Rust-Westinghouse air blown gasifier with hot gas cleanup.



- Type Gasifier
- Air/O_2
- H_2O Quench/Heat Recovery

- Hot
- Inbed/External
- Gas Polishing

- Atm/Pressure
- Fuel Utilization
- Combustion Temp.
- SOFC Parametrics

- Adv. Comb. Turbines
- Non-Reheat/Reheat
- Plant Size

Figure 3-1 — IG/SOFC Simplified Block Schematic.

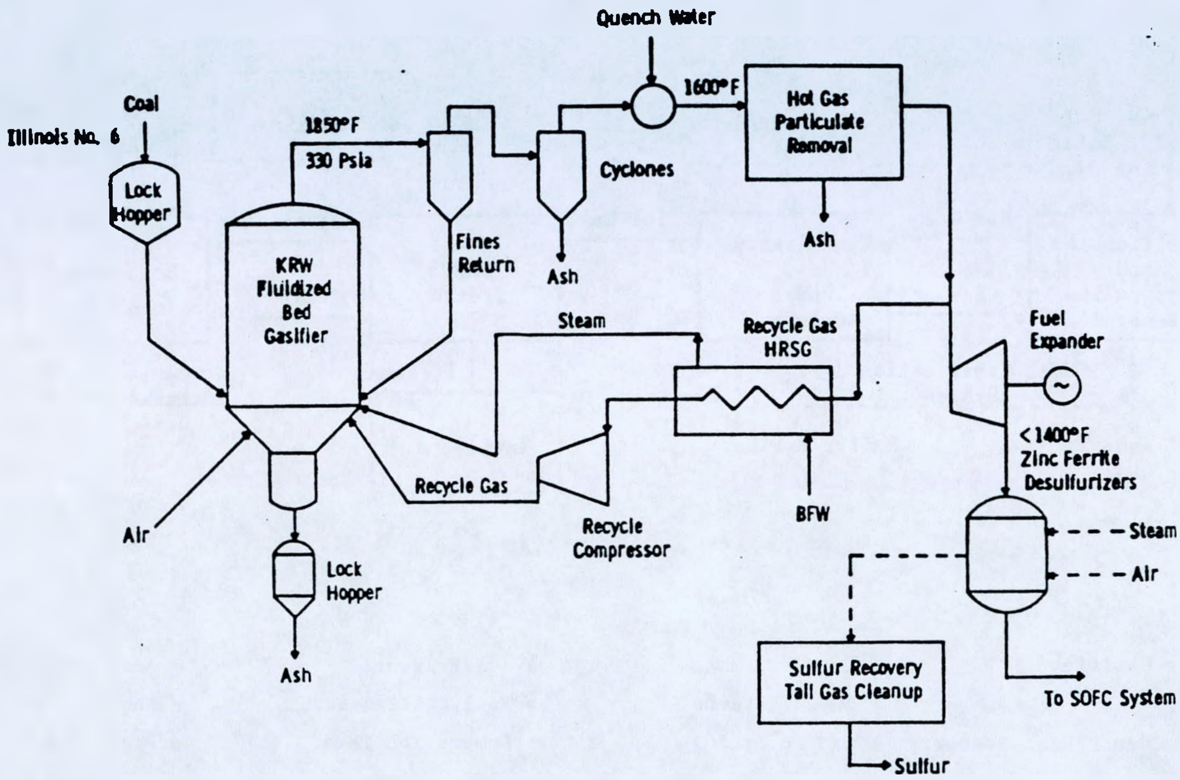


Figure 3-2 — Flow Schematic of SOFC Systems Model for Fluidized Bed Coal Gasifier Subsystems with External Desulfurization.

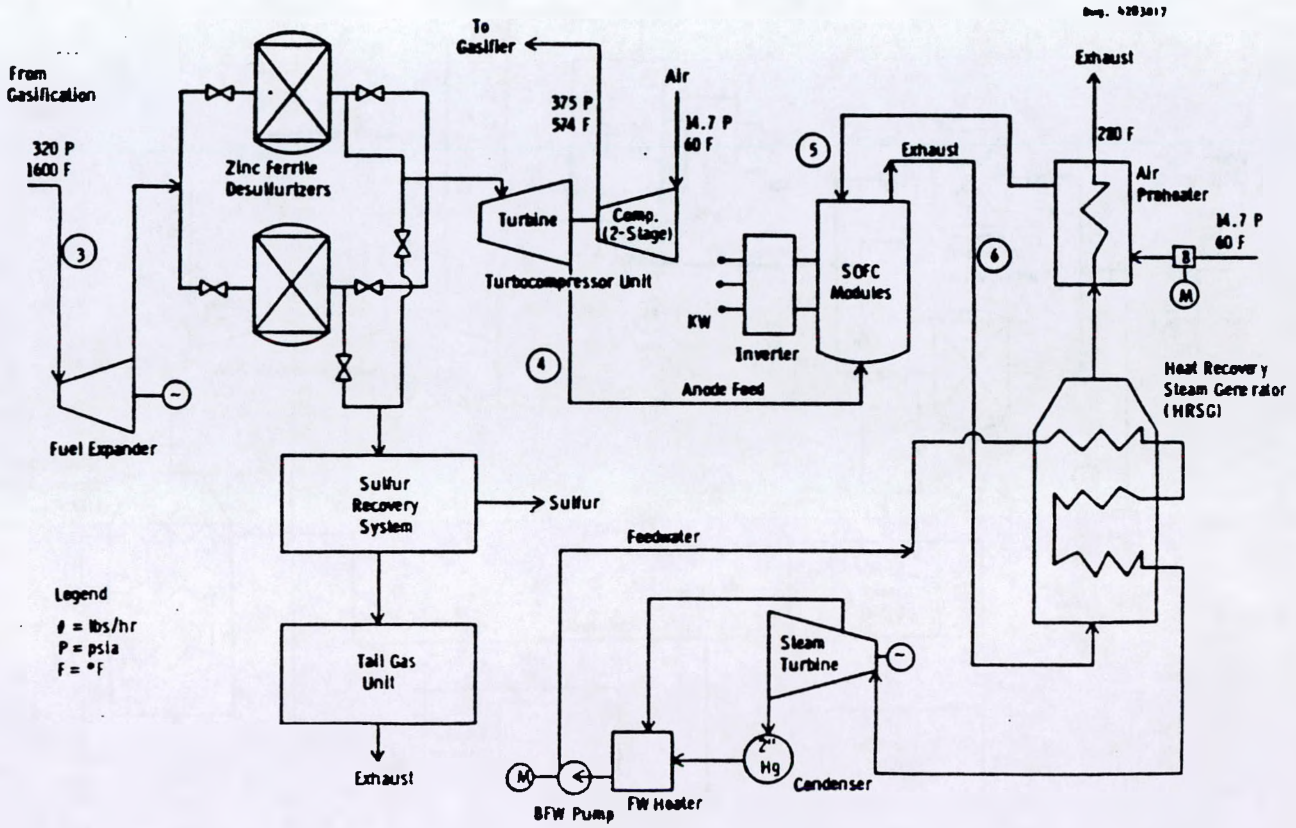


Figure 3-3 — Modular IG/SOFC Power Plant Gas Cleanup/SOFC Flow Diagram.

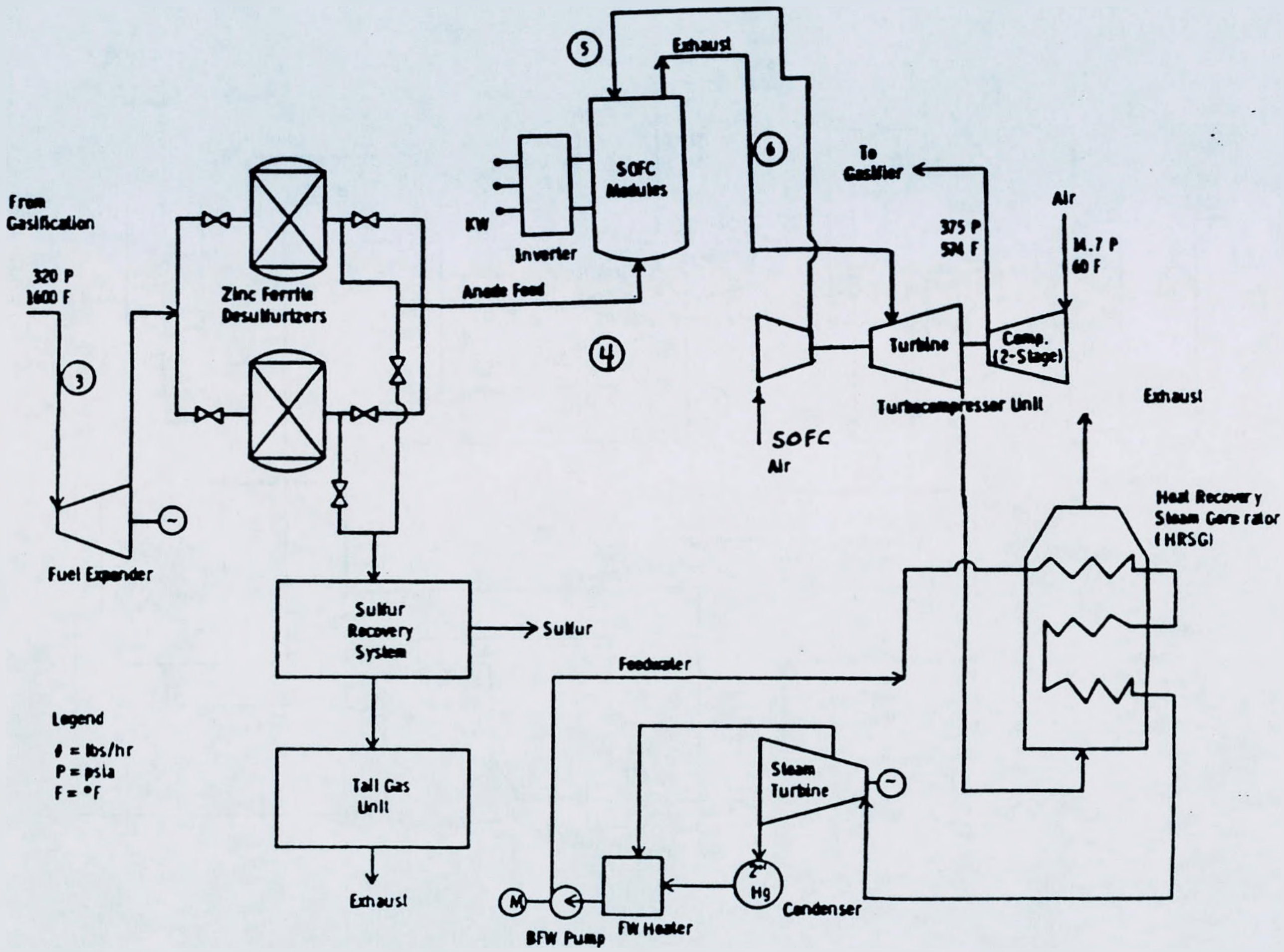
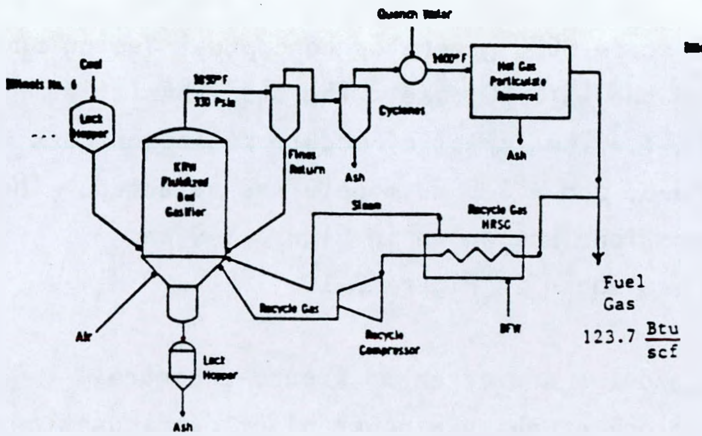
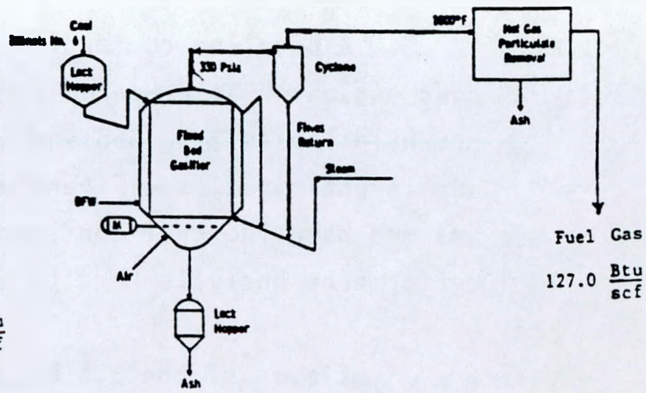


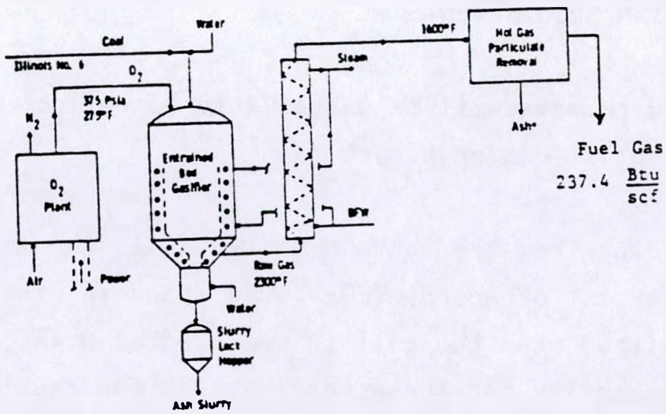
Figure 3-4 — Modular IG/SOFC Power Plant Gas Cleanup/SOFC Flow Diagram.



-a-



-b-



-c-

a. KRW Gasification System with Recycle and Steam Production.

b. Lurgi Fixed Bed Gasifier.

c. TEXACO Entrained Bed Gasifier with Radiant Fuel Gas Cooler.

Figure 3-5 — Comparison of Coal Gasifiers for SOFC - Power Systems Applications.

Sensitivity and trade-off studies were initiated. It was demonstrated that heat rate decreases with increasing fuel utilization in the IG/SOFC case, Figure 3-6 and that the temperature of the gas exiting the SOFC module increases as the fuel utilization is decreased Figure 3-7.

A baseline commercial scale SOFC generator conceptual design and cost estimate was prepared for the IG/SOFC case. The study basis is shown in Tables 3-5, 3-6 and 3-7. The impact of module rating on cost was investigated, see Figure 3-8, and a 3.5 MW module was selected. The assumed baseline cell configurations are shown in Figure 3-9 and performance analysis results are shown in Figure 3-10.

Eleven of the 3.5 MW modules are arranged around a central exhaust duct to form a power block on which a power plant configuration can be constructed. This power block concept is shown in Figure 3-11.

3.3 ESTABLISH COMPONENT DESIGN REQUIREMENTS

Component design requirements will be established to reflect the results obtained in the conceptual design effort.

One illustrative finding from the above noted study is the impact of cell voltage on the cost of energy (COE). As shown in Figure 3-12, the minimum COE is realized when the cell is operated at 0.48 volts. It illustrates the necessity for these total system studies in order to make informed judgments on individual component development programs.

3.3 ESTABLISH DETAILED DESIGN

Work under this subtask will begin at a later date.

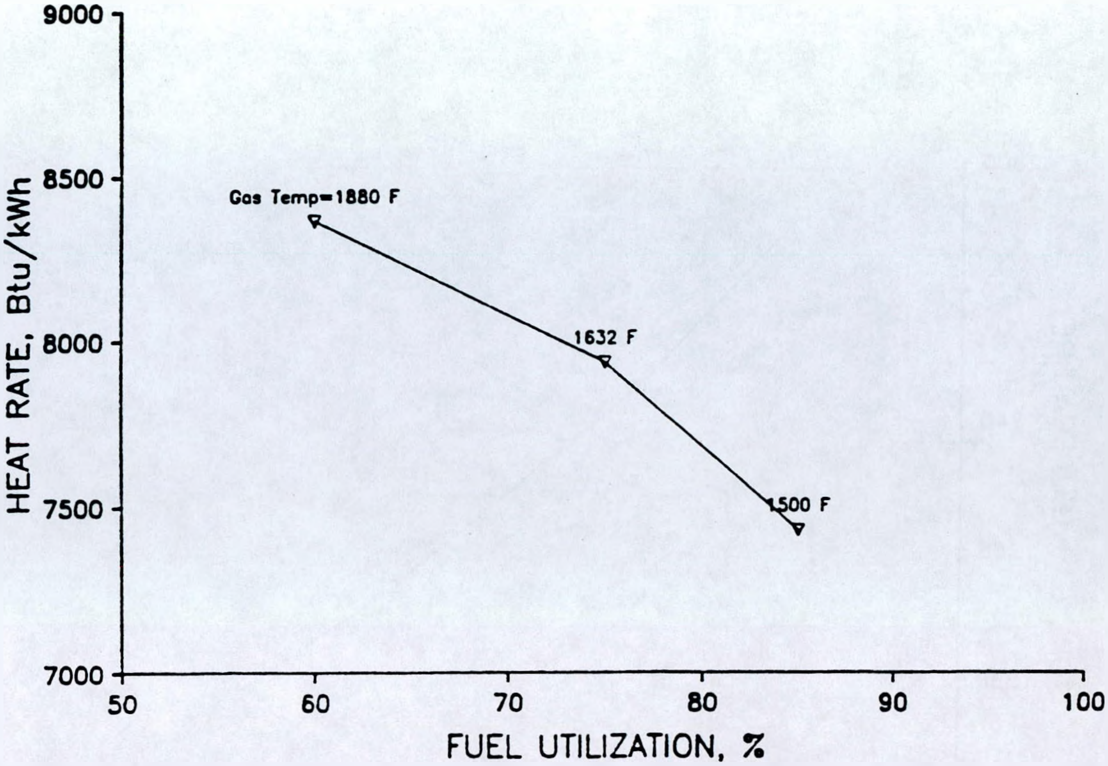


Figure 3-6 — Plant Heat Rate vs Fuel Utilization
for IG/SOFC (1 atm/600 mV) 200 MW Plant.

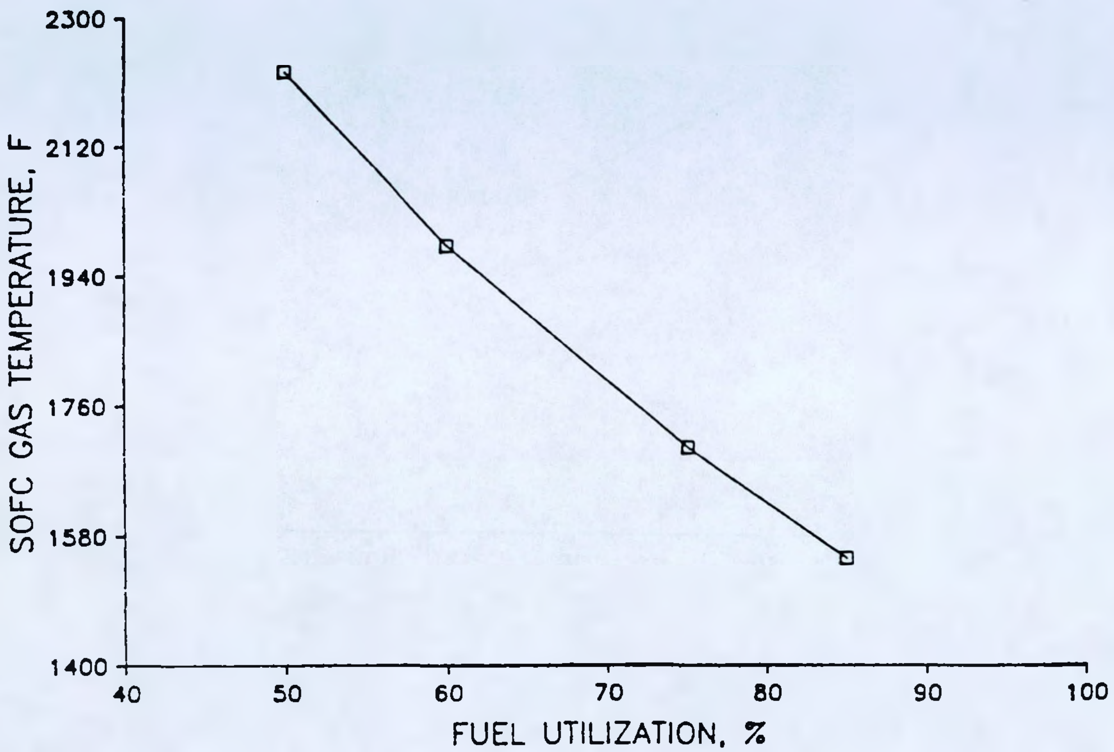


Figure 3-7 — Effect of Fuel Utilization
SOFC Gas Temperature (10 atm).

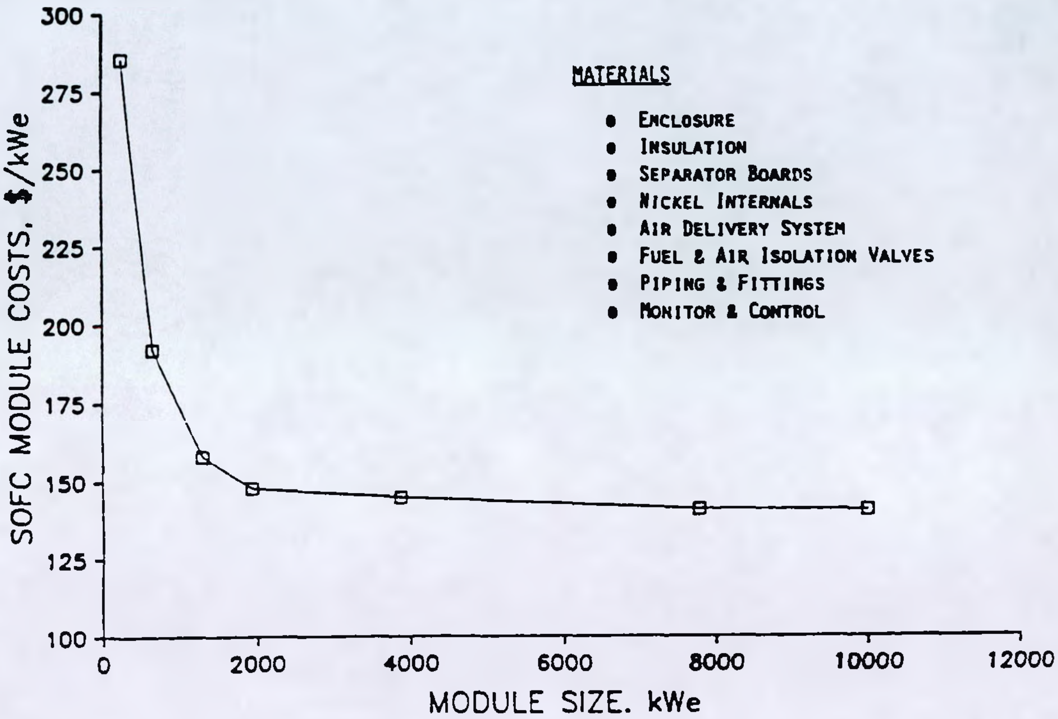
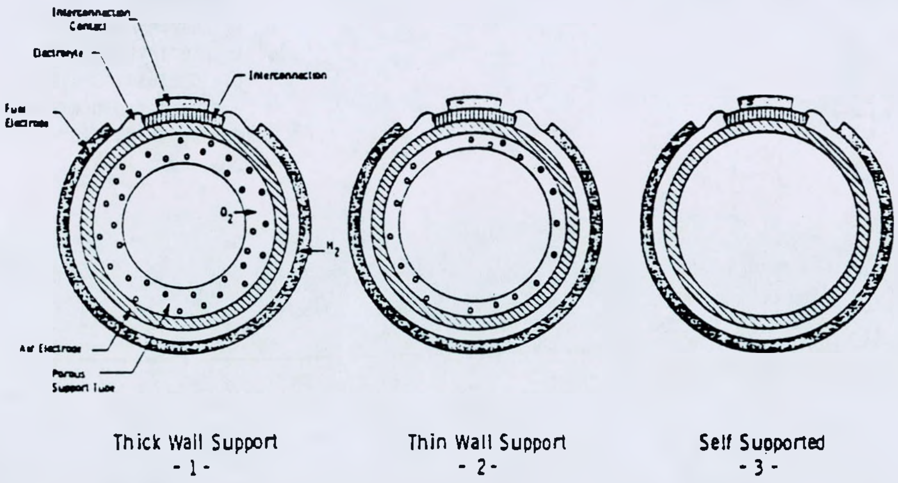


Figure 3-8 — SOFC Enclosure Costs vs Module Size.

	1	2	3
Cell ID (cm)	0.884	1.056	1.192
Support Tube Tk. (cm)	0.203	0.120	NA
Air Electrode Tk. (cm)	0.108	0.108	0.157
Cell OD (cm)	1.534	1.534	1.534
Power (watt/ft-1 atm)	21.0	24	37



SOFC development steps

Figure 3-9 — Baseline Cell Configurations.

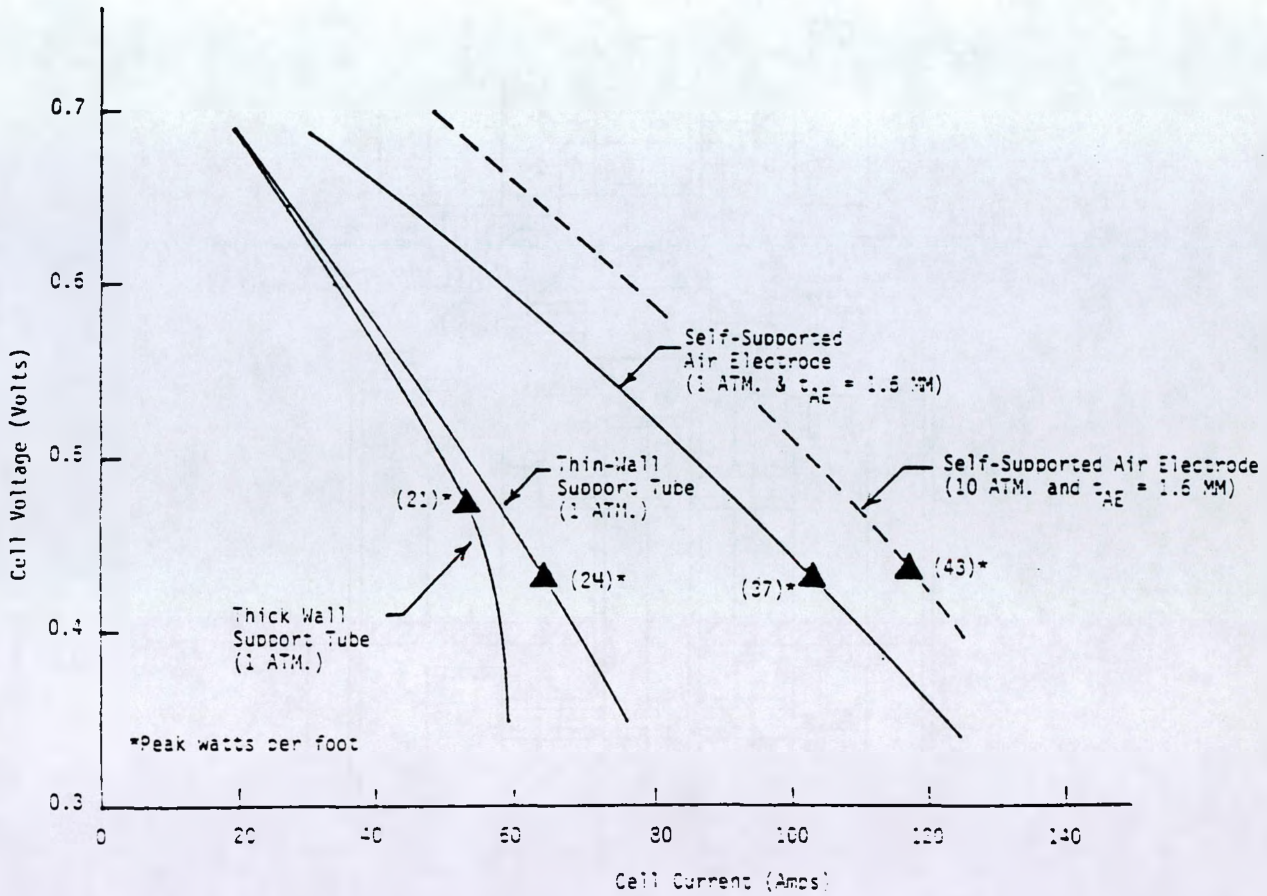


Figure 3-10 — V-I Curves for Different Fuel Cell Designs.

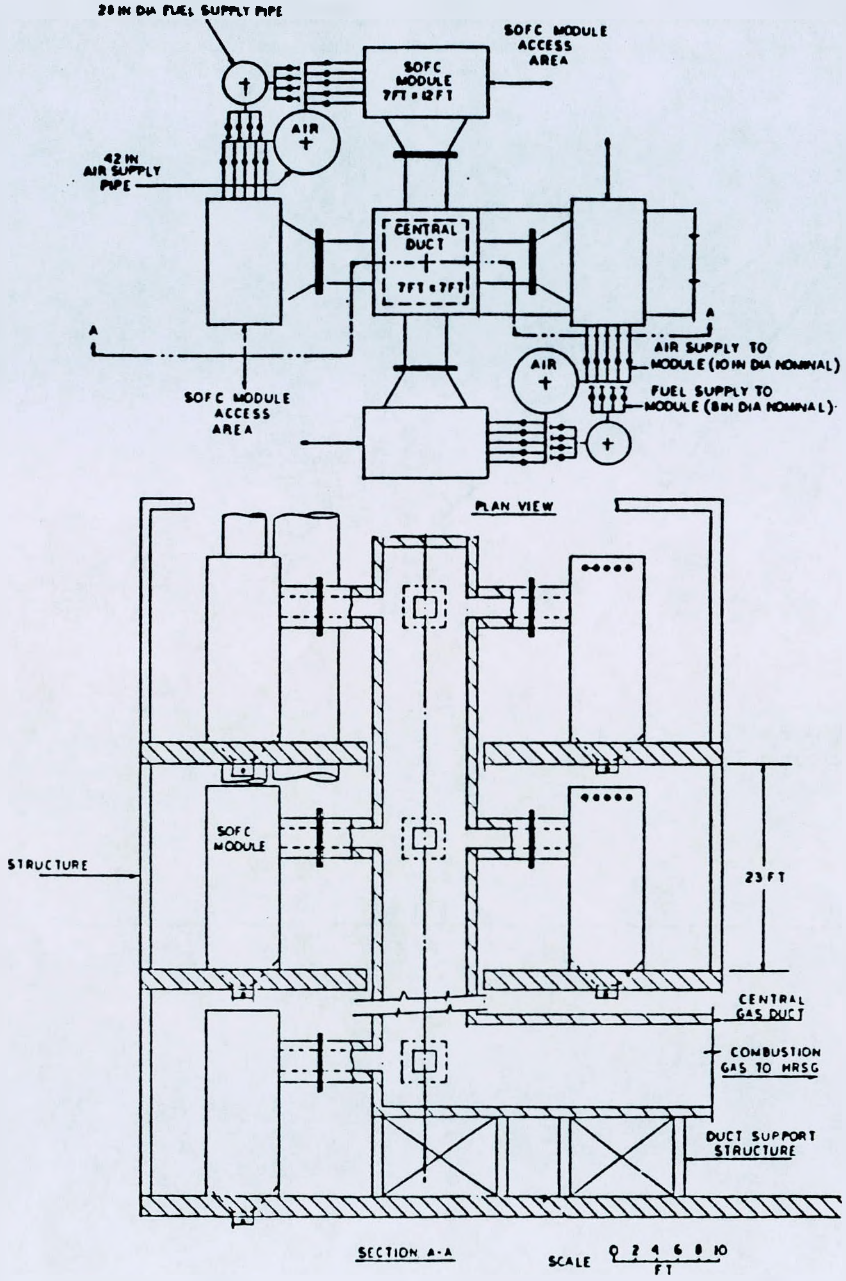


Figure 3-11 — Layout of SOFC Modules Illustrating Integrated Building Block Arrangement.

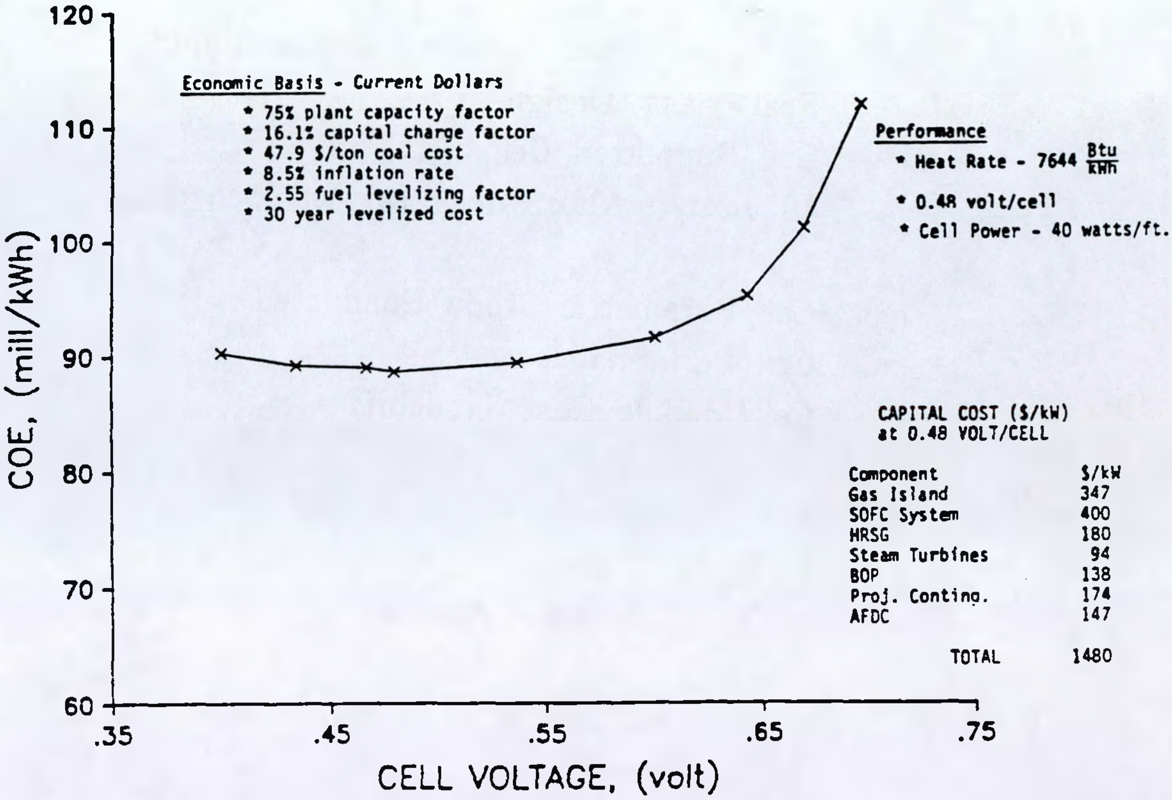


Figure 3-12 — IG/Atm SOFC Cost of Electricity - Cell Voltage Parametrics.

Table 3-5 — Basis of Commercial Scale SOFC Generator Conceptual Design and Cost.

- Assumed Basic Tubular Configuration
  Seal - less Design
  Self Supported Cell
  40 watt/ft Max Power (at 0.5 inch dia.)

- Cell Parametric Study Conducted
  Cell Performance
  Cell/Module Cost Tradeoffs

- Cell Production Facility Costed
  EVD Technology
  10,000 Cell/Day Capacity

- Conceptual Design of SOFC Module
  Truck Transportable
  Field Serviceable (modular)

Table 3-6 — Design Requirements for Truck Transportable SOFC Module.

Physical (not to exceed)

- Width x Length: 12 ft. x 55 ft.
- Height: 12 ft.
- Weight: 82,000 lbs.

Rating

- Fuel - Coal Gas
- Power (max) - 3.5MW (at 0.48 V/cell)

Operating Parameters (at 85% utilization)

- Fuel Flow - 24,000 lb/hr
- Fuel Temperature - 780° F
- Air Flow - 90,320 lb/hr
- Air Temperature - 715°F

Table 3-7 — Cell Reliability and Module Design.

Basis:

- 1/10,000 per year cell failure frequency (goal)
- One cell failure results in loss of module and requires isolating module for repair.
- Module size established on cell failure rate and cost tradeoff.

4.0 WBS 10 -- IMPROVE AND VERIFY CELL PERFORMANCE

This task, Task 2 of the work scope, is intended to encompass the development, verification and fabrication of the cells for a multi-kW module suitable for a 25 to 200 kW generator. The requirements and design are to be delineated in the course of execution of Task 1. The module, utilizing these cells, is to be developed and verified in the course of execution of Task 3.

This task is divided into nine subtasks reflecting major areas of activity necessary to improve and verify cell performance, including: 2.1 Develop Cell Fabrication Facility, 2.2 Air Electrode Development, 2.3 Fuel Electrode Development, 2.4 Interconnection Development, 2.5 Support Tube Development, 2.6 Model Development, 2.7 Cell Test Facility, 2.8 Cell Test Plan and 2.9 Test Cell Life and Performance. These are discussed herein in subsections 4.1 through 4.9.

Two tests were conducted on a 5 kW generator in the previous phase of the program. The results from those tests define a baseline for the cell technology improvement effort. The cells and module of that generator have been treated as a resource for investigation of operational impacts. Two hundred eighty-eight cells were operated, in the generator environment, and subjected to two thermal cycles (room temperature to 1000°C to room temperature) for more than 400 hours. Seventy-two cells were operated through one thermal cycle. The generator environment covered a wide range of conditions; e.g., temperatures were measured over the range of 900 to 1140°C. The 324 cells that make up the stack for this module are shown in Figure 4-1. This photo taken when the stack was removed at the end of the first test, shows the very dark cell (in the upper left hand corner) that was in the most obvious distress.

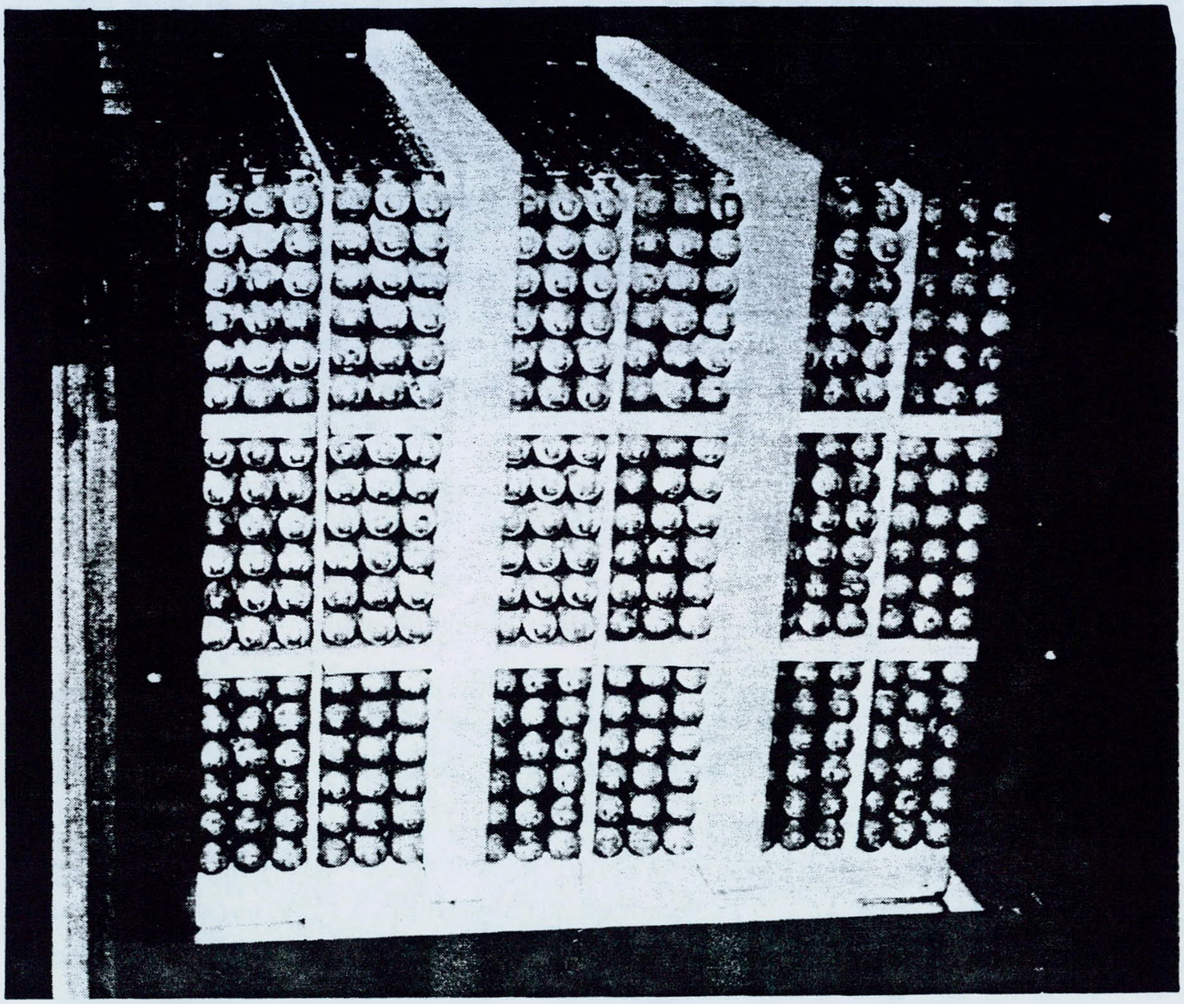


Figure 4-1 — End View of Disassembled 5 kW Generator.

A major thrust of the project during this reporting period has been the systematic teardown and examination of the the 5 kW generator and its cells. Implications of the cell investigation have provided important direction to the development discussed in this section. Module implications of the examination are discussed in section 5.0. The investigation of the cells was focused on three time related objectives:

- Causes of catastrophic failure during the first few hundreds of hours of operation, e.g., a cracked cell and/or a significant leak near the closed (fuel entry) end of the cell that could cause a chemical fire. It is believed that the termination of the first test was necessitated by such an incident.

- Causes of relatively rapid degradation of performance that would be of significant concern over the first few thousands of hours of operation, e.g., leaks that grow or produce consequential damage of significance in this time period. It is believed that the termination of the second test was necessitated by such an incident.

- Causes of slow degradation of performance that are anticipated to become significant in the quest for 50,000 hour, or longer, life; e.g., contaminants that are expected to impact the long term performance of the cell components. It is possible that the post-test analysis of the 5 kW generator may shed some light on this type of problem. However, it would be necessary to establish the relationship between short time high temperature operation and long time lower temperature operation before the impact of contaminants (noted in the tear down of the 5 kW generator stack) could be quantified.

The ongoing effort to resolve the problems, after they are identified, can be and is being prioritized. Only a few cracked cells have been observed (4 were found in the 5 kW generator teardown), but this is an area where the effort must be concentrated because the goal must be essentially total elimination for thousands of hours of operation.

Therefore, the most important cell improvement effort is to define and reduce residual stresses in and/or among the components of the cell. Both fabrication processes and operational conditions must be considered to understand their impact on the build-up of stress within the cell.

The identification of causes of early and growing leaks is the second most important priority. It is possible that leaks may lead to cracking of the cell. That is, it is possible that this and the prior effort will merge as the work progresses. The resolution of leaks in finished cells, or leaks that appear early in cell operation, is expected to require advancements in cell material and/or process specifications or in the implementation of those specifications in cell fabrication. These may also require advancements in stack and module technology, as discussed in Section 5. The predominant location of the cell leaks is observed to be associated with the interconnection and its interface with the electrolyte. The evidence suggests that it will be important to carry out extensive and intensive investigation of the materials and processes used in interconnection fabrication.

An effort has been mounted to identify possible causes of stress in the fuel and air electrodes. It is recognized that stress, introduced by other cell components, may show up in cracks along the junction between the interconnection and the electrolyte if it represents an area of relatively low strength.

The causes of long term degradation that will ultimately determine the economic life of cells and modules are still largely conjecture. Thermodynamic analyses indicate the potential of very long life, possibly up to 100,000 hours. Cells have been operated for thousands of hours in single-cell stands. Test cell #123 has accumulated 5400 hours, as of March 30, and continues on test. The evidence suggests that development will be required in proving cells that are less sensitive to the contaminants or in eliminating the contaminants or some acceptable combination of the two. Potential contaminant sources include those found in fabrication source material (silicon, aluminum, zirconium), the fuel (sulfur) and the module components such as insulation (silicon, aluminum).

The examination of the 5 kW generator is essentially complete. The cells selected for destructive examination are indicated in Table 4-1. All of the cells were vacuum leak tested. The leak test technique provides a useful comparative indication of cell integrity. Boroscope examination of 144 cells identified one cracked cell. Seven cells were radiographed and four were found to be cracked. One hundred and six cells were examined for the location of leaks with leak sites determined on 65 cells, most at the interconnection borders. Four had leaks on the closed ends. The cells with high leak rates were generally located near failed cells that had become very hot. The interconnection leaks were associated with mechanical damage and interconnection degradation. The more severe interconnection degradation occurred where contaminants were identified.

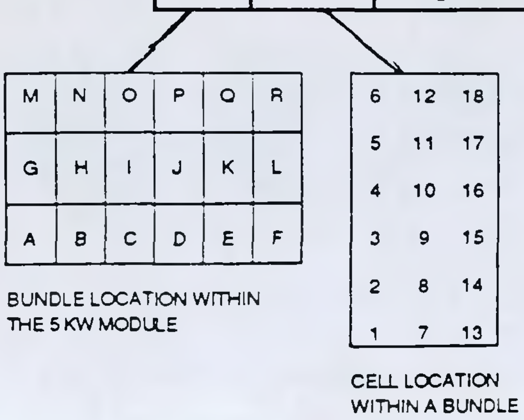
4.1 DEVELOP CELL FABRICATION FACILITY

A Pre-Pilot Facility (PPF), capable of the fabrication of 225 kW/yr of cells and modules, is being designed and constructed by Westinghouse. The facility is scheduled for completion and checkout in time to initiate production of the cells for the multi-kW stack, on or about October 1, 1988.

The definition of the materials and processes applicable to the PPF is being continued in parallel with the design and procurement effort. The single-cell and twelve-cell fabrication equipment, extant from prior programs, are being used in this investigation.

Table 4-1 — Cells Selected, from the 5 kW Stack, for Destructive Examination.

Bundle	Position	Attributes for Selection
A	18	Very low leak rate, 7.5 mm Hg/min
B	15	High leak rate, 138 mm Hg/min
C	8	Long. crack; High leak rate after 1st test, 96 mm Hg/min
M	12	Transverse crack
M	17	Plug end leak, 94 mm Hg/min
K	7	Plug end leak, 44 mm Hg/min
P	10	High leak rate, 126 mm Hg/min; Possible IC degradation
P	16	Long. crack; Close to bundles failing in 1st test
P	17	High leak rate, 58 mm Hg/min
P	18	Transverse crack
I	2	Moderate leak rate, 11 mm Hg/min; Possible IC degradation
I	8	High leak rate, 84 mm Hg/min; Inside row near center of stack
I	14	Moderate leak rate, 21 mm Hg/min
R	5	Plug end leak, 31 mm Hg/min; From new bundle (2nd test only)
R	7	Plug end leak, 200 mm Hg/min; From new bundle



Extensive review and update of the cell fabrication processes and equipment were carried out during this period. These were partially funded by this project and partially by Westinghouse. Examples of typical tasks include:

- Air electrode slurry control by elimination of entrained gas in the slurry and improved temperature control.

- Fuel electrode slurry control by modification of the dipping process and by storage environmental control.

- Fuel electrode stress reduction by development of additives for the reduction of fuel electrode shrinkage as temperature is applied.

- Adoption of microhardness measurement technique to evaluate air electrode quality after sintering.

- Flow modeling of the conditions in the Electrochemical Vapor Deposition (EVD) reactor leading to modification of the chlorides delivery equipment, which feeds the source materials into the process.

- Investigation of residual stresses in as fabricated cells.

Development work is proceeding in a number of areas where the progress to date justifies continued pursuit of the potential even though the status is not adequate for inclusion in the current cell production process. Examples include:

- Development of a new single-cell test envelope with the objective of expanding the temperature range of the test equipment.

* AC Impedance (or Dielectric Parameter) tests at low, and perhaps room, temperature and correlation with high temperature test results.

* Resistance probe method for detection of circumferential air electrode cracks.

* Evaluation of ultrasonic procedures to detect cracks in cells.

Residual stress, in cell components, measurements were initiated using a two dimensional strain-gage rosette with a central hole. Wide variation in stress measurements, cell-to-cell, were noted and a rough correlation of these stresses with cell cracking during manufacture was noted, as shown in Figure 4-2.

Investigation of cells from a number of fabrication and operational sources indicate a diversity of leak characterization. Leaks have been detected in essentially all locations along the cell, generally along the edges of the interconnection strip. In the case of the 5 kW generator, the preponderance of these leaks were observed to lie between 10 and 20 cm from the closed end of the cell, which may indicate a correlation with the current density. This correlation is further supported by the observed higher leakage from cells in the central (of three parallel paths) position in the strings of the 5 kW generator. It is now known (see Section 5) that these cells were located in a relatively higher fuel flow and hence are assumed to have carried greater current compared to their two parallel cells.

Leaks have been observed at the closed end of the cell. These are particularly worrisome because they consume fuel before it has reached the active portion of the cell. This impacts efficiency (at the best) and places the operation of the cell in a less than planned fuel

Dwg. 4284B73

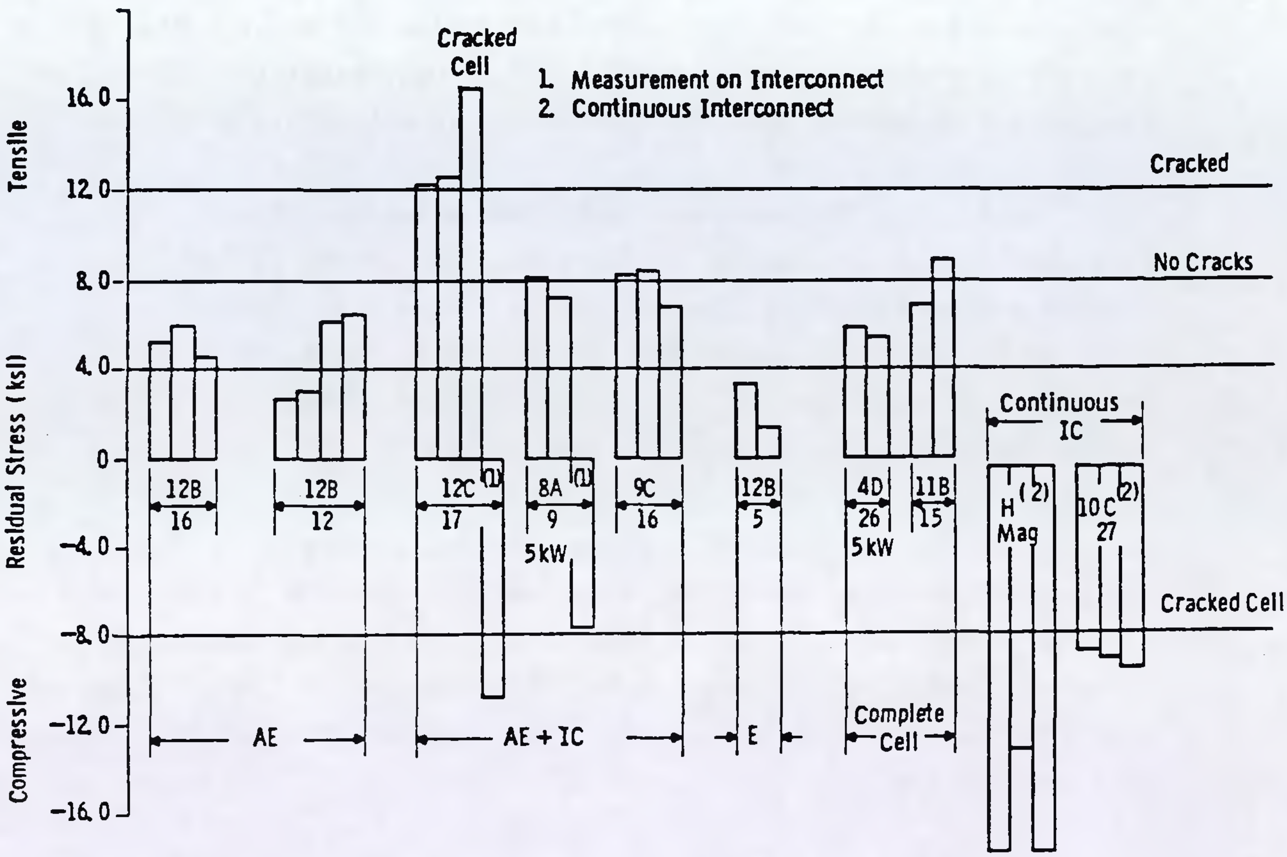


Figure 4-2 — Cell Stress Characteristic Observed During Manufacturing.

utilization condition, which may damage the cell (at the worst). The leak responsible for termination of the first 5 kW test was of this character.

A computerized data base and data management system is being established for the cell fabrication activities and areas. Methodology for data retrieval and manipulation are being implemented. Data from past cell fabrication is being transferred into the data base.

A Digital Equipment Genvax System is being utilized. RSI language is used for ease of manipulation. Important design considerations included: The ability to handle large quantities of data, rapid input and convenient recall, and analysis capability to offer ease of manipulation, if required. Input of data is facilitated by computer terminals at each fabrication area.

The quality program is being extended to keep pace with the changing emphasis as the solid oxide fuel cell program is advanced from a research laboratory effort toward an engineering and manufacturing oriented (commercial) effort. A full time manager of Product Assurance was added to staff, replacing the on-loan manager that had been provided by Power Systems.

Methods and techniques for quality control are being developed. A temperature cycle, prior to sintering the cells into bundles, appears to offer a non-destructive technique for evaluation of completed cells. Investigation of AC impedance (or Dielectric Parameter) as a possible room temperature cell quality control technique was initiated and is continuing.

Quality and investigative equipments, that have been utilized during the past year, include: Scanning Electron Microscope, Boroscope, Stereo microscope, Closed-end Bennert-type U-tube mercury manometer, MKS type-227A Baratron pressure gauge, with an MKS Model PDR-C-1B digital readout and a VeeCo mass spectrometer-type helium leak detector.

4.2 AIR ELECTRODE DEVELOPMENT

Vendors for lanthanum manganite powder, the source material for air electrodes, have been identified. Programs are underway to assist these vendors in the interpretation and application of the stringent powder specification. Purity and particle size/distribution definitions are receiving prime attention. These characteristics impact the deposition process and are believed to be important factors influencing the polarization and coefficient of thermal expansion of the finished air electrode.

As mentioned above, a program was mounted with Westinghouse funding to refine the air electrode slurry deposition equipment and essentially eliminate temperature change and gas entrainment during deposition.

A limited effort was expended on the development of the technology of an air electrode that may prove adequate, in the longer term, to serve the additional function of support for the cell structure (eliminating the porous support tube). A cell was produced using essentially the conventional EVD process and representing a major milestone. The cell was tested, even though it was known to have a significant leak, for 165 hours. The result that it could only be operated at an apparent fuel utilization of up to 70 per cent was expected. The voltage achieved, 600 mV, indicates problems with one or more of the cell components. Hence, additional development will be required for successful application of this promising concept.

4.3 FUEL ELECTRODE DEVELOPMENT

The investigation of the cells produced for and operated in the 5 kW generator revealed difficulties in applying the slurry, deficiencies in adhesion of the fixed electrode and indications of residual stresses.

The fuel electrode is applied to the cell by slurry dipping. The choice of liquid for the slurry, the characteristics such as viscosity, the environment in which the dipping and drying takes place and even the details of masking of the cell are all considerations in the production of successful electrodes. Refinements have been realized in all of these areas during the past year.

Shrinkage of the fuel electrode, prior to EVD fixing with the zirconia skeleton, has caused failure to achieve full attachment in some cases. Work is underway to identify dopants, such as zirconia, that may be incorporated into the slurry and reduce the shrinkage. A few (one to five) per cent addition can reduce the shrinkage by an order of magnitude as shown in Figure 4-3, but it appears that a penalty (as much as 4X) must be accepted in the resistivity of the resulting electrode. Continued development to refine the requirement and minimize the resistance will be required.

4.4 INTERCONNECTION DEVELOPMENT

The investigation of the 5 kW generator strongly implicates the interconnection and its interfaces as the area of concern about leaking and cracking cells. Leaks have been observed in the interconnection region in as fabricated cells, in cells that have operated in generators for a few hundred hours and in single cell tests after thousands of hours. The leaks are observed to increase in magnitude with operating time.

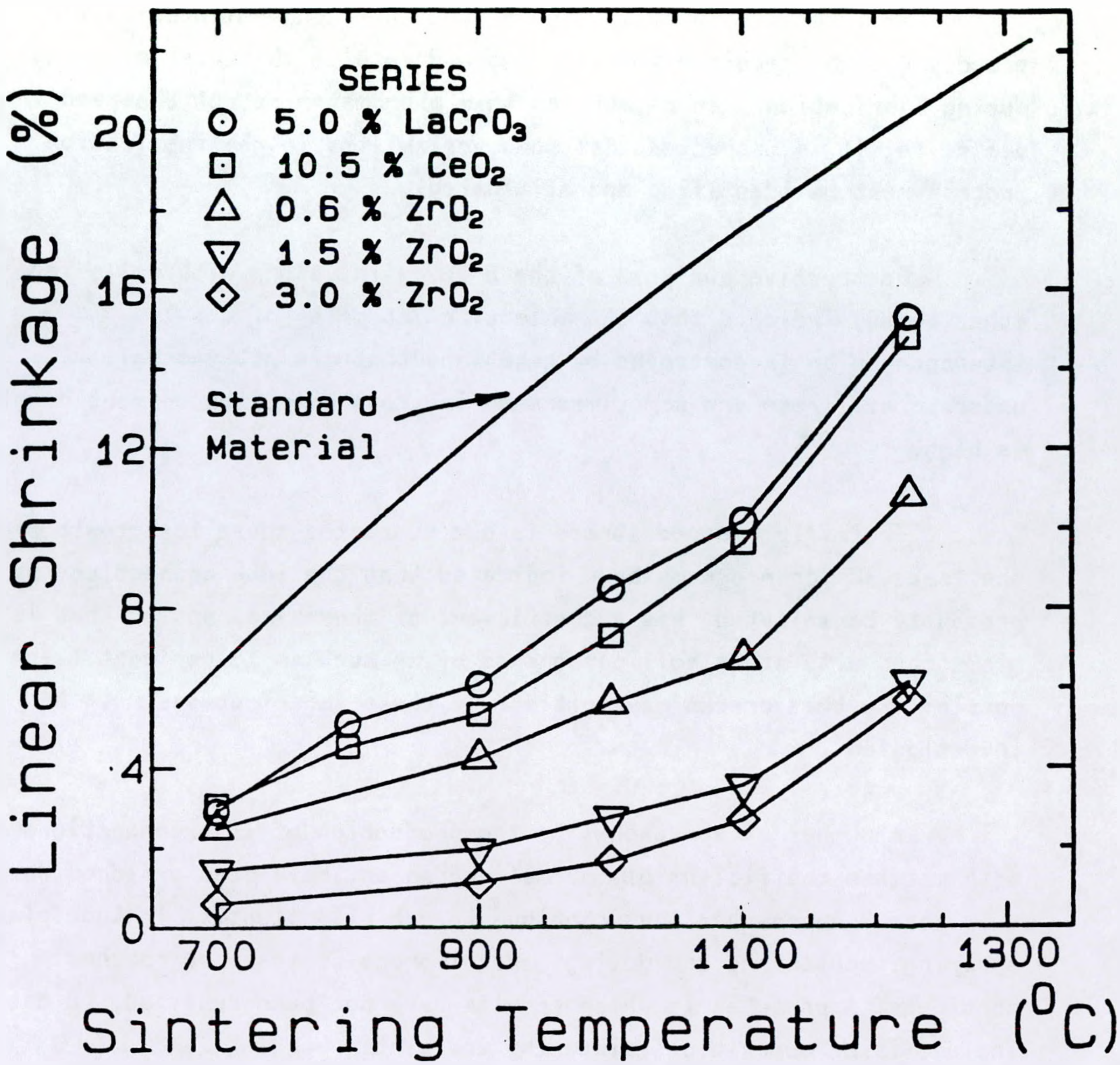


Figure 4-3 — Fuel Electrode Shrinkage vs Sintering Temperature for Various Dopants.

An intensive investigation of the interconnection deposition process will be required to determine and resolve the cause of leaks during fabrication. In as much as this phenomenon is not observed in all cells, it is suspected that some variability in the fabrication process must be identified and eliminated.

Destructive analysis of the 5 kW cells, along with cells from other tests, indicate that the molecular integrity of the interconnection is destroyed by reactions that are not yet well understood. These are sometimes seen in areas where the current density is high.

Thermally induced stress is one suspected cause for growth of the leaks. Prior programs have indicated that the interconnection, as presently constituted, has a coefficient of thermal expansion that is mismatched with other cell components by as much as 15 per cent. The possibility that cracks may initiate at these imperfections must be investigated.

A number of approaches to the production of interconnections, with matched coefficient of thermal expansion, have been explored during this year. Approaches that continue to exhibit potential include plasma spraying, sputtering and doping. Development of these approaches continues. Approaches in which results have not been realized, to date, include laser deposition, sintering and sinter bonding.

A second important characteristic of the interconnection is the room temperature resistance. This determines the degree of ease or difficulty with which nickel is plated onto the interconnection for the purpose of attaching the cell-to-cell electrical connection. It also figures into the overall cell resistance (at operating temperature) and hence into the efficiency of the module. It was determined that magnesium doping, in very small amounts, can reduce the resistance by many thousands of ohms. Efforts to incorporate other dopants (strontium, cobalt and manganese) were not successful. Magnesium doping was developed and incorporated during the year. Since magnesium doping does not contribute to resolution of the mismatch in thermal expansion, it must be considered a stop-gap solution and the other directions must be pursued in the future.

4.5 POROUS SUPPORT TUBE

The identification and qualification of vendors for support tubes has been carried on during the year. Candidates are providing tubes of the thin (~1 mm) wall configuration for evaluation.

Tubes, from two vendors, have been processed into finished cells that have been tested in the single-cell test stands. The initial test results tend to confirm results from our analytical model indicating a 30 per cent advantage in peak power per unit length of cell for thin versus thick (2 mm) wall.

Work with the candidate vendors will be continued to assist their efforts to meet all tube specifications.

4.6 MODEL DEVELOPMENT

The model development effort during the past year has included that required for the conceptual design and engineering studies of the cells, modules and systems that are discussed elsewhere in this report.

Stress analysis techniques have been modified and are being applied to the investigation of residual stresses in the cell. These are being correlated with the destructive investigation discussed in section 4.1.

4.7 CELL TEST FACILITY

Requirements for the up-coming new single-cell test stands were influenced by the results of the 5 kW generator investigation. For example, concepts for operation at higher temperature, with controlled axial temperature profile and with measured axial current distribution have been identified. Design and partial construction of five new stands have been accomplished during this year. Completion of the construction is anticipated by June of 1987.

Proof testing of the new cell fixture concepts will be carried out.

4.8 CELL TEST PLAN

The anticipated cell testing requirements were explored and these formed the basis for preparation of a general cell test plan for the remainder of the contract.

The tests can be grouped in three general categories: Design evaluation, production/processing improvements and operational limits.

Examples of design evaluation tests, conducted during this period, include those performed on the cells with thin-walled support tubes and the test of the cell constructed on a self-supported air electrode.

Examples of production/process improvement tests include testing of the cells with higher yttria in the fuel electrode fix and cells with magnesium doped interconnection.

Examples of operational limit tests include tests to determine stability of performance at near peak power and long term (life) tests.

4.9 TEST CELL LIFE AND PERFORMANCE

Fourteen single cell tests have been performed during the period.

The listing of cells tested is presented in Table 4-2, indicating the area of investigation in each case. A listing of pertinent test data, relating to these same cells, is presented in Table 4-3.

Table 4-2 — Cells Tested at Temperature.
Results are Presented in Table 4-3.

Cell #	Major Experimental Variable
108	One of the electrical qualification tests during fabrication of the 5 kW generator, maintained on life test.
114	Same.
121	Investigation of quantity of fuel electrode nickel slurry.
122	Evaluation of fabrication process following numerous modifications; see subsection 4.1.
123	Investigation of fuel electrode fix temperature, cell was maintained on life test.
124	An effort to simulate fuel starvation, a suspected cause of failure in the 5 kW generator.
125	Investigation of quantity of yttria on stabilization of the fuel electrode.
126	Same (Cell from different fabrication group).
127	Same (Cell from same fabrication group as #125) to attempt to confirm poor performance shown in #125.
128	Investigation of stabilization of both fuel electrode fix as well as electrolyte, maintained on life test.
129	Same as #125 (Cell from still another fabrication group).
130	Evaluation of cell concept depending on the air electrode for structural support.
131	Investigation of dopant of the interconnection, seeking increased electrical conductivity and improved thermal expansion match.
132	Evaluation of vendor-supplied thin-walled porous support tube.
133	Investigation of current density, in interconnection, on material stability.
134	Same.

Table 4-3 — Cells Testing Summary. Major Experimental Variables are Presented in Table 4-2.

Test Number	Leak Rate, Initial (mm Hg/min.)	Initial Cell Resistance (approximately 100h, Ω cm²)	Final Cell Resistance, Ω cm²	Initial, Watts/cm² (approx. 100h)	Final Watts/cm²	Total approx. hours at temperature (in chronological order): 1000°C	1100°C	1200°C
				1000°C St'd. Fuel Gas 250 mA/cm² 4 stoichs. air 85% Utilization				
108	--	.53	.74	.156	.148	1720		
114	--	.56	.90	.156	.149	4800		
121	0.0	.56	.51	.151	.158	265		
122	--	.54	.49	.152	.152	100		
123 (f)	0.40	.60	.60	.155	.156	1250		
		.51	.52	.159	.159		212	
		.41	.47	.150	.150			70[a]
		.67	.67	.152	.152	450[b]		
		.70	.78	.149	.135	3300		
124	1.0	.51	.50	.161[d] .120[e]	.134[e]	328		
125	4.4	.98	1.04	.146	.139	242		
126	<0.5	.54	.54	.151	.151	85		
127(f)	<0.5	.96	1.1	.147	.130	450		
128(f)	0.7	.54	.62	.156	.152	2855		
129(g)	0.7	.60	.63	.152	.150	185		
130	324.	.45	.38	.141[h]	.158[i]	150		
131	0.3	.68	.66	.150	.157	835		
132	0.8	.96	.48	.159	.29	550		
133	0.3	.54	.51	.157	.160	695		
134	0.1	.66	.61	.153	.159	692		

Footnote key:
- (a) Furnace element burnout forced cool-down; partial element repair.
- (b) Including one thermal cycle to room temperature (R.T.).
- (c) Restart in test stand #5.
- (d) Basis = 55 cm^2 ("open" area).
- (e) Basis = 110 cm^2 (including "blocked" area).
- (f) Continuing test.
- (g) Westinghouse-sponsored-test.
- (h) 61% F.U.
- (i) 65% F.U.

NOTE: page 52 is blank.

5.0 WBS 11.0 -- DEVELOP AND VERIFY STACK PERFORMANCE

This task, Task 3 of the work scope, is intended to encompass the development, fabrication and verification testing of a multi-kW module for a 25 to 200 kW generator. The requirements and design are to be delineated in the course of execution of Task 1.

The task is divided into four subtasks reflecting major areas of activity necessary to improve and verify module (stack) performance, including: 3.1 Develop Stack Fabrication Facility, 3.2 Develop Stack Hardware, 3.3 Stack Test Plan and 3.4 Test Stack Life/Performance. These are discussed in subsections 5.1 through 5.4.

The investigation of the module from the 5 kW generator was focused on three areas:

- Differences between design values and operational measurements,
- Performance of the insulation, including release of contaminants, and
- Indications of desirable instrumentation in future test articles.

The 5 kW generator was designed to be a demonstration of performance of a small module. The instrumentation was that desired for operation and control. It proved adequate for the intended purpose. Performance at levels up to 5.3 kW was well documented. However, it was inadequate for the thorough investigation of the life/reliability problems that were identified in the course of the test.

The temperature profiles measured in the generator were skewed to one side. Investigation of the generator revealed no cause for this other than the chemical fire resulting from leaking cells. There was no evidence of faulty thermocouple data. It would be desirable to have a more detailed thermal map.

The fuel flow distribution was not measured during operation. Deviation from design was hypothesized from the evidence including temperature profile, bundle voltages within the stack, and the distribution of leaking cells after operation.

Room temperature flow distribution measurements were made. These included tracer and smoke techniques. Extensive analytical effort has also been directed to the understanding of the fuel flow. A notable feature of the problem is the relatively low fuel gas velocity. The evidence indicates that the fuel flow was high around the central cell of the three cells in parallel in the string. It also indicates that the flow was not uniform across the stack, being higher in the outer regions of the module. Model studies of the fuel flow distribution through plenum and stack configurations in future modules are indicated.

The practical module insulation material candidates are limited. Commercial insulations, of interest for very high temperature SOFC application, contain small quantities of materials that may be deleterious if released and fuel transported to the cells. Insulation materials must meet several criteria in addition to thermal resistivity, e.g., workability, electrical resistivity, mechanical stress and wear tolerances.

Insulation samples from the 5 kW generator were examined in an attempt to isolate potentially harmful contaminants that might have been released. The results have been inconclusive.

The potential value of increased instrumentation was emphasized by the many post test analysis questions for which answers could only be hypothesized by analysis and interpolation. This suggested the desirability of building one or more highly instrumented facilities.

The evident differences between test results from the single-cell tests and the module tests raise the question of how to improve the correlation between the two. Test cell #114 (see Figure 5-1) was one of the qualification cells for the 5 kW production. This cell was maintained on test for more than 4700 hours. Destructive examination at the end of the test revealed very little indication of the types of deterioration observed in the 5 kW test after 400 hours.

Other instrumentation improvements under consideration include additional voltage taps. The voltage across each of the 18 bundles (made up of 3 x 6 cells) was measured. It is recognized that individual cells may be excessively distressed without adequate warning from the bundle voltage and additional voltage taps, especially in experimental devices, would be valuable.

Efforts to replicate failure mechanisms seen in the 5 kW tear-down were unsuccessful. A cell was operated with one half of the fuel electrode covered to simulate fuel starvation. The cell operated normally in spite of deliberate high fuel utilization, high current density and a distorted temperature profile. A cell was operated at 1100 and then at 1200°C. Some degradation was noted at the higher temperature. The test was terminated by failure of the test equipment. The cell was returned to test and has survived more than 5000 hours with degradation of about 10 mV/khr.

5.1 DEVELOP STACK FABRICATION FACILITY

The capability to produce the multi-kW stack is being incorporated into the Pre-Pilot Plant. Effort related to this subtask is included in the preparation for the Pre-Pilot Plant and discussed under Task 2, Subtask 1.

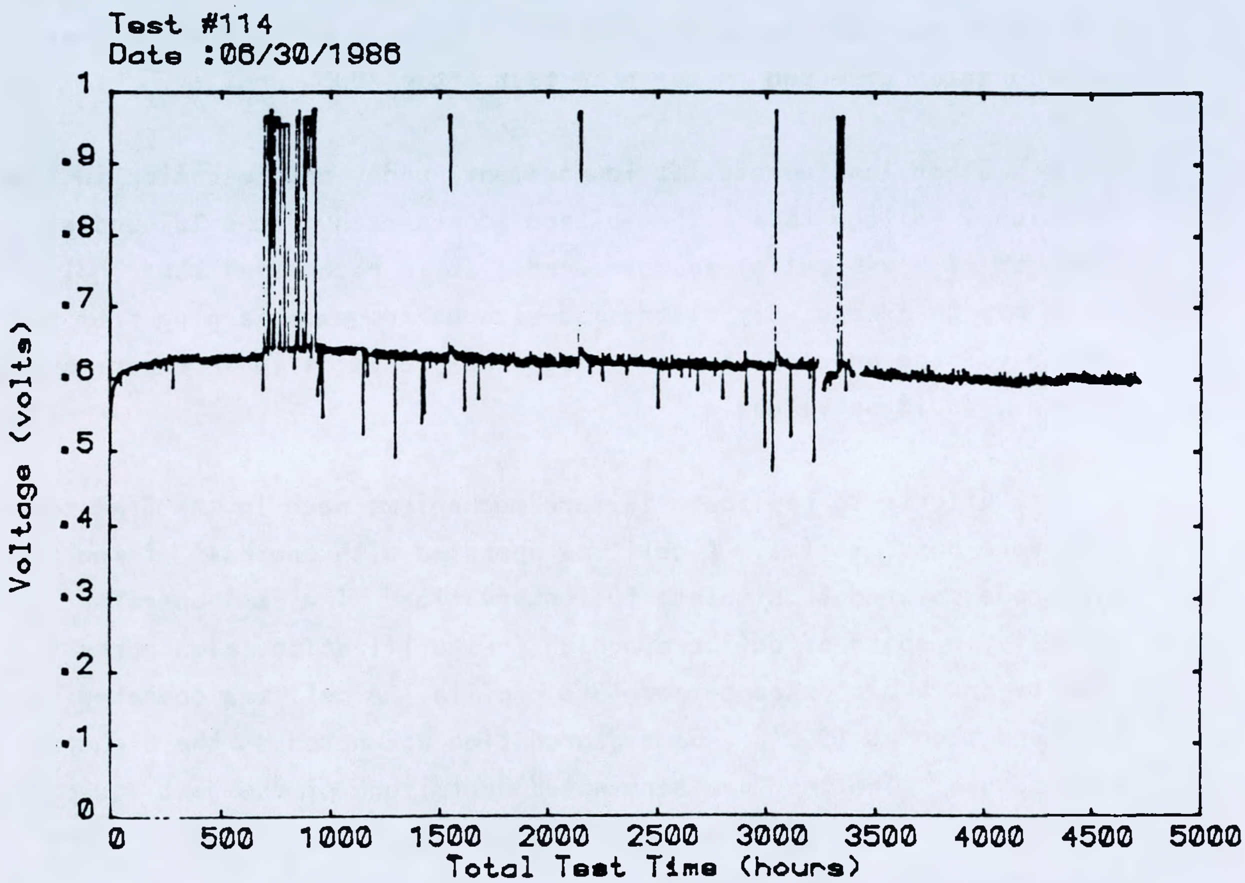


Figure 5-1 — Voltage vs Time Curve for Test Cell #114.

5.2 DEVELOP STACK HARDWARE

Investigation of alternative insulating materials is indicated and was initiated. Alumina and zirconia materials, processed in various ways and forms, are being evaluated in terms of release of potentially harmful (to the cell) release of contaminants or constituents.

Conceptual designs for highly instrumented bundle tests were prepared. Various possibilities for implementation of this concept were considered. It was decided that a bundle test facility should be constructed and operated. Such a facility is now under development and will be constructed by Westinghouse. The goal is to be able to handle bundles of cells up to a rating of about 1 kW. The instrumentation is to include some 50 moveable probes that may carry temperature measuring detectors or gas sampling tubes. These may be located within the air and fuel streams as they pass along the cells and can be moved to produce continuous vertical and horizontal data profiles. Extensive voltage measurement is also planned.

The first test is visualized as a combination of shake-down and extension of the investigation of the 5 kW cells by using 36 cells (two 3 x 6 bundles) that were in the 5 kW stack.

5.3 STACK TEST PLAN

No work during this period.

5.4 TEST STACK LIFE/PERFORMANCE

No work during this period.

NOTE: page 58 is blank.

6.0 SUMMARY PLAN FOR THE NEXT PERIOD

The overall objective for the next year is to define the multi-kW stack. To this end, it will be necessary to:

- Continue to develop the reference design for IG/SOFC plants.
- Continue development to resolve the cell and module problems identified in the operation and post-test-investigation of the 5 kW generator.
- Complete the Westinghouse Bundle Test Facility.
- Design and perform experiments, in the bundle test facility, to confirm the selection and design of the multi-kW generator. Particular emphasis will be placed on understanding the life related phenomena and on identifying potentially deleterious conditions.
- Select the cell and module for the multi-kW stack. One option being considered is a cell, built on the thin-walled support tube, with a 50 cm active length, and with improved components, e.g., an interconnection with at least a 50 per cent reduction in thermal mismatch. This cell is expected (extrapolating data from tests of 36 cm cells on thin-walled support tubes) to produce 40 to 50 watts. A stack of 24 x 24 (32 bundles of 3 x 6) cells, therefore should produce a module of nominal 25 kW rating. The final selection will depend on success in the development program, notably in the planned bundle tests.
- Develop the specific cell and module, including resolving those deleterious conditions identified in the bundle tests.

- Perform design effort germane to the multi-kW stack Design Review.

- Continue the construction of the Westinghouse pre-pilot plant in order to be prepared to produce the cells and module for the multi-kW stack in 1988.

- Maintain an appropriate level of development effort on cell and module aimed at timely realization of performance, reliability, life and economic goals, as defined in Task 1.