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PROGRAM PLAN

FOR

MOLTEN CARBONATE FUEL-CELL SYSTEMS DEVELOPMENT

MASTER

FOSSIL ENERGY
DEPARTMENT OF ENERGY

TRW Energy Systems
Group
McLean, Va

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ABSTRACT

The purpose of this document is to describe in both programmatic and technical terms the methodology that the U.S. Department of Energy will use to commercialize a molten carbonate fuel cell power plant. Responsibility for the planning and management of the program resides in the molten carbonate fuel cell program office at the Argonne National Laboratory which reports to the Assistant Director for Fuel Cells in the Division of Fossil Fuel utilization of DOE/FE. The actual development of technology is carried out by selected contractors. The technology development phase of the program will culminate with the construction and operation of two demonstration power plants. The first power plant will be an industrial cogeneration plant which will be completed in 1987. The other power plant will be a baseload electric power plant to be completed in 1989.

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Part I Program Plan

1. INTRODUCTION

1.1 NATIONAL ENERGY GOAL AND STRAIEGY

Many of the national energy goals which are being addressed by the U.S. Department of Energy (DOE) can be met by the implementation of fuel cell technology. Present day conventional technology has an efficiency of approximately 33 percent; whereas, fuel cell technology is estimated to have an efficiency of up to 50 percent. The widespread utilization of the fuel cell technology over conventional technology would bring about a decreased consumption of fossil fuel, including oil and gas.

Two different types of fuel cells are being developed by DOE, i.e. phosphoric acid and molten carbonate. A program has been initiated for each of the two applications of the phosphoric acid fuel cell: electric utility dispersed powerplants, and on-site integrated energy systems. The Molten Carbonate Fuel Cell Program, which is the subject of this plan, will extend the range of applications to include industrial cogeneration and baseload electric power generation. In addition to being an energy-efficient technology, the molten carbonate fuel cell powerplant is a coal-utilizing technology which will increase coal consumption and, therefore, increase oil savings.

The molten carbonate fuel cell powerplant will help to resolve environmental objections to the increased use of coal because the fuel cell technology inherently does not produce NO_x . Also, sulfur is removed in a gas cleanup subsystem of the powerplant before the gas enters the fuel cell, decreasing SO_2 emissions to acceptable levels.

1.2 OBJECTIVES

The objective of the Molten Carbonate Fuel Cell Systems Development Program is the earliest feasible commercial use of clean, highly efficient coal-fueled molten carbonate fuel cell powerplants. A primary program goal is the operation of a commercially feasible coal-fueled baseload plant of 50 percent efficiency by 1990.

This goal would be accomplished through the completion of the following specific objectives:

- o Development of a fuel cell powerplant - Tasks required to fulfill this objective are: perform system tradeoff and design studies; fuel cell stack scale-up and development; and verification of fuel cell stacks and other components of the powerplant.
- o Cogeneration application test - Design, construct, and test a molten carbonate fuel cell powerplant for industrial cogeneration.
- o Baseload application test - Design, construct, and test a molten carbonate fuel cell powerplant for baseload electric generation.

2. SYSTEM DESCRIPTION

2.1 MOLTEN CARBONATE FUEL CELL POWERPLANT

The molten carbonate fuel cell powerplant concept is a system composed of a simple coal gasifier, fuel gas cleanup system, a fuel cell subsystem to convert the energy of the gas to electricity, an inverter, and a bottoming cycle, such as a steam turbine, to scavenge the heat generated by the cells and gasifier and enhance the electrical output. Figure 1 is a schematic diagram of a large baseload fuel cell powerplant. Because the cells are efficient and operate at a high ($\sim 600^{\circ}\text{C}$ or $\sim 1200^{\circ}\text{F}$) temperature, which allows their waste heat to be recovered, the total system efficiency can be very high - approximately 50 percent from coal to electricity. Sulfur is removed as H_2S from the gas before it enters the cells, a much easier and more effective process than scrubbing SO_2 from combustion products, and NO_x is not formed because there is essentially no combustion. The result is a highly efficient coal-fueled electric powerplant of very low pollution. The system just described will have wide application and benefits in purely electrical generation. If the bottoming cycle is eliminated, high grade heat becomes available for such uses as industrial process heat or for district heating. These cogeneration applications can result in effective efficiencies much greater than 50 percent.

It has been estimated¹ that the commercialization of molten carbonate fuel cell technology could, in the year 2000, save between 612,000 and 2,775,000 barrels of oil per day. The major market areas that were considered

¹"A Brief Summary of Potential Benefits of Fuel Cell Applications", Draft Report, Samuel H. Nelson, February 21, 1978.

Figure 1. Large Baseload Plant Schematic

were electric utility and industrial cogeneration. Other markets that were considered were aluminum industry, total energy systems, and pipelines. These market areas comprise less than five percent of the above energy savings.

2.2 MOLTEN CARBONATE FUEL CELL

Molten carbonate fuel cells share the desirable characteristics of fuel cells in general, scalability; low pollution; high efficiency; etc., but differ from other cells in two important ways which result from their high operating temperature ($\sim 600^{\circ}\text{C}$). The first difference is that kinetic processes are fast, which means that voltage losses are low, cell efficiency is high, and carbon monoxide (a poison in low temperature cells) is a fuel in molten carbonate cells. The second difference is that the heat removed by cell cooling is at a high temperature, which allows its practical use in bottoming cycles or for industrial cogeneration.

Figure 2 is a conceptualized drawing of one repeating element in a stack of molten carbonate fuel cells. Fuel enters the cell in a plane parallel to the anode which is a porous nickel structure filled with electrolyte and reacts at the anode-electrolyte interface. The CO in the fuel can react as shown in the anode reaction, but a more favored path is via conversion to hydrogen by the shift reaction followed by consumption of the hydrogen.

The shift reaction is rapid at cell temperature in the presence of the metallic cell components, and becomes increasingly favored as H_2 is depleted and H_2O builds up in the fuel stream moving through an operating cell.

The cathode's structure is similar to the anode but is composed of NiO. The cathode gas, as can be seen from Figure 2, is a mixture containing CO_2 and oxygen. The CO_2 must come from the spent anode stream, and there are two general ways of transferring the CO_2 . The simplest is to burn the spent

Figure 2. Cell Schematic

anode stream with excess air in a catalytic burner. The oxidant so obtained tends to be rather dilute, especially if the anode stream contained nitrogen. It also may be possible to separate CO_2 and water from the anode stream by use of a so-called product exchange device (PED). The separation is easy in principle, several processes are available, and the benefit in terms of cell voltage is considerable. The decision to develop and use a PED is like the decision to use oxygen-enriched cathode gas, in that it is a question of system cost versus system efficiency for the entire powerplant.

2.3 INTER-SUBSYSTEM REQUIREMENTS SPECIFICATION

In order to ensure the commercial viability of the fuel cell powerplant, the entire powerplant must be designed and tested. But the development effort of this program is directed toward the molten carbonate fuel

cell. Prior to the integration of the subsystems (gasifier, cleanup, fuel cell, inverter, and waste heat utilization) powerplant system tradeoff and design studies will be performed to optimize the system. Based on the effects of fuel gas impurities on the fuel cell, a gasifier-cleanup combination will be chosen for study and test. Except in the case of the Multi-MW Pilot Plant, which will use gases derived from oil, the prototype powerplants will require full-size dedicated coal gasifiers. The utilization of the fuel cell waste heat can impact the gasifier and cleanup subsystems. But the major application of the waste heat will be in process heat, a bottoming steam cycle, or a gas turbine cycle. Information of fuel cell developments and requirements will be made available to the programs which are developing the other technologies that will be used as subsystems in the fuel cell powerplants.

3. CURRENT TECHNOLOGY SITUATION AND COMMERCIAL STATUS

Significant accomplishments have been achieved in the development of the molten carbonate fuel cell. Many problems which have been encountered during cell testing have been solved. Although the goals for performance and life have not yet been reached, recent development has made large strides in reaching these goals, and it appears that these goals can be met with further development. Tasks which have been undertaken to decrease cell cost and define and increase contaminant tolerance have been effective and are continuing.

The major parameters of the status of fuel cell technology development are discussed below together with the achievements to date.

Performance

Once a voltage goal has been selected, power density is maximized (i.e., the cell area is reduced) to minimize the cost of electricity. The goal for power density is 125 W/ft² at 0.85 V. Recently over 100 W/ft² has been achieved in pressurized tests, and the goal level appears well within reach.

Life

Subsystem life is also cost-related, since long replacement intervals are economically necessary. The stack goal is 40,000 operating hours between major overhauls (cell replacement) under operating conditions. Although 40,000 hours have been accumulated on laboratory-type cells, life remains a significant area for development. The duration of the longest test run with realistic bench-scale cells was 16,000 hours. This test was terminated by seal corrosion, a problem which appears to have been solved.

Cell Cost

The important aspects of cell cost are materials and manufacturing cost. Raw material costs appear to be inherently fairly low and the synthesis of LiAlO_2 has been greatly simplified recently. Hot-pressing, which is still utilized, is a relatively undesirable mass production method. Work is planned to develop improved mass production methods and is scheduled to be implemented by 1983.

Contaminant Tolerance

Recent results suggest a nominal fuel sulfur limit of 1 PPMV. The actual operating level may be greater or less than 1 PPMV, depending on configuration of the cell/cleanup interface and the CO_2 recycle system. Additional work is required to establish corrosion effects and higher sulfur tolerant electrodes.

The majority of the work being performed on the development of the fuel cell is being funded by the DOE. It is estimated that without this government assistance, there would be no major development of the fuel cell and thereby virtually preclude the commercialization of the Molten Carbonate fuel cell powerplant.

4. TECHNOLOGY DEVELOPMENT NEEDS

In order to meet the program objectives of commercial deployment of molten carbonate fuel cell powerplants, the technology development needs can be met in the following steps.

Fuel Cell Development & Scaleup

This is presently the primary activity of the program. Continuous cell development and testing are being carried out in small, relatively inexpensive cells. The results are directly applied to larger cells and to short cell stacks, then full-size stacks. Stack operation is used to verify design and performance; to provide realistic thermal and mechanical cell environments, and to test scale-dependent factors, such as operation at high voltage off ground. The approach of developing technology in small-scale followed by scaleup minimizes the cost and risk associated with necessary large-scale testing because many of the test parameters have been verified in advance. For example, cell function and performance are established with 10-Watt cells prior to test of 2-kW short stacks, and satisfactory short stack operation is planned before test of 100-kW full-size stacks.

In addition to developing the current design of the fuel cell, work is being done to develop technical options for the fuel cell which may prove to be more reliable and cost effective. New materials are being developed for the anode which may increase performance and lower production costs. In addition, new electrodes are being explored which may have a higher resistance to sulfur contaminants. Development of the cathode includes activities which are aimed at increasing the strength and structural stability of the cathode material. Different production processes are being investigated for the cathode,

anode, and the electrolyte tile in order to reduce costs. Also, new configurations for the fuel cell and new metals for cell hardware will be assessed.

A new process of distributing gases within the fuel cell in order to increase cell life also is being studied.

Tests will be performed on the cell using simulated and actual coal gases. These tests are performed to ensure the performance and the reliability of the fuel cell when operated on coal gases. These tests will also provide data on the tolerance of the fuel cell to various levels of contaminants.

System Tradeoff and Design

The final product of the system tradeoff and design work is an optimized reference design for the first powerplant constructed for each application. Earlier work will provide: a list of users requirements and other constraints; a set of subsystem goals and requirements, especially for subsystems requiring development, such as the fuel cell subsystem, and the gasifier cleanup subsystem; a reference design based on this list including an evaluation of the characteristics of each subsystem; and a periodic update based on technological progress and any changes which may occur in user requirements or other constraints. This work is required for each application, although there is very extensive commonality of technology.

Test and Verification

A workable fuel cell package and stack will first be established before the test and verification work is to commence. All the repeating elements (cells) and other components of a module of multicell stacks, and the stack itself, will be designed to have the proper compatibility, mechanical properties, reliability, thermal management and cycling capabilities, etc. to function in the anticipated duty cycle, throughout design module life (now set at

40,000 hr). The contaminant tolerance of the fuel cell and stack must be understood as well as the tolerance of the cell and the design of the gasifier cleanup subsystem.

The goals and requirements developed during system design are used to indicate the need to develop or adapt existing technology. Major subsystems (e.g., the coal gasifier-cleanup subsystem) will not undergo significant development within this program, but development of smaller subsystems and integration hardware (e.g., cell CO₂ transfer loop) is undertaken. The first activity to be undertaken will be to test stacks with coal gases from a gasifier-cleanup subsystem. This test will require the physical connection of the fuel cell to the fuel processing subsystem (gasifier-cleanup) and will test the operating characteristics of the fuel processing subsystem in conjunction with the performance of the fuel cell subsystem.

Once acceptable results are received from that test, the fuel cell subsystem will be scaled up to a Multi-MW Pilot Plant. In order to construct the Multi-MW Pilot Plant, a large number of fuel cells will be required. A manufacturing process that is compatible with mass production will be developed and the manufacturing capability will be established. The data from the pilot plant along with the results from the coal gas stack test will be used with other available subsystem data to verify the total system. The subsystem compatibility will be established based on the test data, and the basis for decision on the commitment to a demonstration power plant will be established.

Demonstration

Two demonstration plants are presently planned: industrial cogeneration application and baseload electric power plant. The conceptual design for each plant will be developed before funds are committed. After a commitment is

made, the final designs will be developed and the fuel cell manufacturing capability will be established. When the power plant has been constructed and checked out, the operation of the plant will be turned over to the host user.

5. PROGRAM ELEMENTS AND FLOW

Figure 3 is a simplified logic network for the development of the molten carbonate fuel cell powerplant. A more detailed logic diagram is shown in Part II. The network is aggregated into four phases of development:

- o Exploratory Development - The work performed in this phase has two main objectives: fuel cell and stack development, and system design and studies. Cell development, which is currently in progress, will continue in order to improve cost, performance, and life. The cells also will be tested on simulated and actual coal gas to identify and quantify the effects of fuel gas contaminants. The cells also will be improved to increase the tolerance to contaminants. Application studies will be performed and requirements for those applications will be determined. Based on those requirements, possible system configurations will be determined and the availability of compatible subsystems (other than the fuel cell) will be assessed. Studies will be performed and a reference design will be selected for each market application.
- o Technology Development - The coal gas testing will be scaled up and the reference designs will be optimized. The coal gas stack test will produce data on the performance of the fuel cell stack when operated in conjunction with a gasifier-cleanup subsystem. The compatibility of the two subsystems will also be tested. Data from this test plus information from other cell and full-scale tests will be used to optimize the reference designs which will eventually be the basis of the conceptual design for the demonstration plants.
- o Engineering Development - The coal gas stack test will have been operating before funds for the Multi-MW Pilot Plant is committed. If the results from the coal gas stack test shows that the fuel cell subsystem will perform with a fuel processing subsystem, the fuel cell subsystem should be tested in a large-scale pilot plant. The data from the Multi-MW test and all of the other tests will be used to verify the system and establish the compatibility of the subsystem.
- o Demonstration - If the subsystems meet the requirements established for the tests which have been described above, and all of the subsystems are verified, a conceptual design will be developed. Two market areas have been identified for a demonstration power plant, industrial cogeneration and baseload electric generation. After the plant is funded, it will be designed, built, checked out, and turned over to the host user for operation. The operation of the plant will provide a data base which will be used to show commercial viability.

The development priorities can be classified into two areas. The fuel cell technology development is a near-term priority with the remainder of the system having a farther-term priority.

Figure 3. Molten Carbonate Fuel Cell Power Plant Program Logic Diagram

In the near-term, cell and stack development is of primary importance. Performance and life are the main concerns; and improvements are needed to produce long-lived electrodes and stable electrodes of high performance. These developments will require greater understanding of electrode processes and of time-dependent changes in the components, especially the electrolyte structures.

As the technology matures, development and adaptation of other system components will become increasingly important. The CO₂ recycle system is a unique ancillary; although processes now exist which can be adapted, CO₂ recycle devices will have to be developed specifically for this purpose. Similarly, fuel processing technology, such as coal gasification and hot gas cleanup, must be chosen and integrated with the fuel cell subsystem into an optimized system which would be demonstrated. The final step after demonstration of the technology development is to commercialize the technology. The strategy for the commercialization plan is shown in Appendix C.

Figure 4 is a work breakdown structure which shows the activities and the tasks associated with each activity. These activities are a disaggregation of the phases which were discussed for the program logic. The Exploratory Development phase has been broken down into Fuel Cell Development and Stack Scaleup and System Tradeoff and Design. The Engineering Development phase has also been disaggregated to show Multi-MW Pilot Plant and verification as two separate activities. Demonstration is divided into the two different powerplants and the commercialization activity.

Figure 4. Work Breakdown Structure

6. PROGRAM SCHEDULING

The research, development, and demonstration efforts of the DOE has been broken down into seven phases. These phases were defined in a memo by Mr. Dale D. Meyers dated May 31, 1978 and titled "Program and Project Management System for DOE Outlay Programs." Figure 5 is based on the information in this memo and shows the phases and key decision points. Further description of these phases is contained in Appendix D.

Figure 6 relates these phases to the activities of the work breakdown structure for the molten carbonate fuel cell program shown in Figure 4. Transition between the phases will require a key decision to implement the next phase of the project and a determination of what direction the project should take. These decision points and other major schedule goals are shown in the milestone chart (Figure 7).

The first major management decision point is the selection of a pilot- (or larger-) size gasifier test site in 1980. This timing is required to enable completion of technical tasks on schedule. The multimegawatt test station scheduled for operation in 1984 will require a decision to commit in 1982. This facility would be a retrofit of a utility-type plant with a molten carbonate fuel cell section. It will use fuels processing and other ancillary technology already developed in the phosphoric acid fuel cell program and will serve as a pilot dispersed generation plant as well as to provide statistical verification of cell section performance.

The key decision points are indicated in FYs 1984 and 1985 for commitment to construction of industrial cogeneration plants and baseload powerplants, respectively. The 1985 decision point allows the construction of the small or large baseload plant on goal schedule. It is based on two experience

Figure 5. Development Phases for New Technology Systems

PHASE 3
EXPLORATORY DEVELOPMENT

- Fuel Cell Development & Stack Scaleup
- System Tradeoff & Design

PHASE 4
TECHNOLOGY DEVELOPMENT

- Coal Gas Stack Tests
- Design Optimization

PHASE 5
ENGINEERING DEVELOPMENT

- Multi-MW Test
- Verification

PHASE 6
DEMONSTRATION

- Industrial Cogeneration Power Plant
- Baseload Electric Power Plant

PRESENT

PHASE 3

3/81

9/79

PHASE 4

5/85

3/81

PHASE 5

5/85

3/84

PHASE 6

12/89

Figure 6. Molten Carbonate Fuel Cell Development Phases

Figure 7. Molten Carbonate Fuel Cell Program Milestone Chart

requirements: about 18 months of multimegawatt level experience in a large test facility, and about 50 months of stack-level experience, some 30 months of which have been on coal gasifier output.

The cogeneration option shows a commitment to construction in 1984. The technological development up to that point is similar to that for the baseload plant. It appears that a 1984 decision point and a 1987 prototype operation are appropriate; this schedule is not yet fixed, pending determination of requirements and constraints which will be developed in FY 1979.

7. MANAGEMENT PLAN

7.1 ORGANIZATIONAL ELEMENTS

Responsibility for the planning and management of the DOE Molten Carbonate Fuel Cell Program resides in the Molten Carbonate Fuel Cell (MCFC) Program Office at the Argonne National Laboratory (ANL). This office reports programatically to the Assistant Director for Fuel Cells in the Division of Fossil Fuel Utilization of DOE/FE. The actual development of technology is carried out by selected contractors.

The MCFC Program Office reports administratively through the Chemical Engineering Division of Argonne National Laboratory and is coordinated with other DOE/FE programs of the laboratory through the Alternate Energy Technology Program Office. The MCFC Program Office relies upon the technical, management, and administrative resources of the Laboratory. Figure 8 shows the management organization of the program.

7.2 MOLTEN CARBONATE FUEL CELL PROGRAM OFFICE

The functions of the Program Office are planning, operating, and control of the Molten Carbonate Fuel Cell Systems Program.

Planning and Budgeting - The objectives, goals, and schedules of the program were developed by the Program Office and are continuously refined and updated as program progress is monitored. The Program Office provides the Assistant Director for Fuel Cells with all necessary program authorization and approval documentation, and budgetary planning and authorization information. Planning and budgeting are based on technical forecasting, inputs from DOE management, inputs from program monitoring activities, assessments of contractor proposals and capabilities, and coordination with other funding agencies, such as GRI, utilities, and EPRI.

Figure 8. DOE - Fossil Energy Division of Fossil Fuel Utilization

Procurement - The Program Office allocates available funding among the contractors to best meet program goals, and prepares complete procurement (Zebra) packages for DOE management approval. Little or no subcontracted effort is processed through ANL. The Program Office shall accept proposals to DOE and shall prepare Requests for Proposals, Program Opportunity Notices, etc. The Assistant Director for Fuel Cells is kept continuously informed of all proposed procurements and their status. Where appropriate, proposals are reviewed by the Technical Advisory Group.

Contracting Arrangements - The Program Office does not have responsibility for contract procurement. Contracts within this program are administered through San Francisco Operations Office of DOE, or via DOE schedule 189.

7.3 MANAGEMENT CONTROL

Contract statements of work will be required by the Program Office to be consistent in content and timing with a logic diagram of the type shown in Part II. Contract reporting requirements shall be based on the DOE Uniform Contract Reporting System¹, and the Program Office shall specify the nature and frequency of reports to be selected from the DOE Reporting Requirements Checklist, form DOE 537 (10/77). Monthly and quarterly technical progress reports shall be distributed.

7.4 APPROACH TO TECHNOLOGY DEVELOPMENT

The primary strategy for development of molten carbonate fuel cell technology is to conduct the majority of development and demonstration efforts on a competitive RFP basis. The contractors must possess the experience and capabilities necessary to develop the technology and to meet a major

¹Department of Energy Uniform Contract Reporting System Guidelines, Vol. VI, January 1978.

powerplant market. The competition fostered by this approach is expected to result in more rapid development and diversity of approach. More importantly, it will provide multiplicity of sources to potential customers.

At present, there is a significant disparity in molten carbonate fuel cell experience among the major contractors, and to ensure the existence of viable competition, it is necessary that each major contractor proceeds on a separate schedule at least until FY 1981. Also, the detailed milestones and decision points are not identical for baseload or cogeneration applications, although the required near-term cell technology developments are indistinguishable. It is expected that all contractors selected for continuation in 1982 will be progressing in accordance with the schedule shown in Figure 7.

Where appropriate, the program relies on supporting contractors that can provide certain special capabilities to the entire program, or can reinforce effort in critical special capabilities to the entire program, or can reinforce effort in critical development areas. An outstanding example of the latter type of effort is the work conducted at the Institute of Gas Technology, which has been and continues to be of major importance in defining and advancing the state-of-the-art.

8. RESOURCES PLAN

The function of DOE involvement in molten carbonate fuel cell development is to hasten technology deployment to meet national needs. The incentive for manufacturer involvement is profit from sale of hardware; this profit is the basic driving force for commercialization. The ability of a business concern to invest in a new technology increases rapidly as the time required until net profit is shown decreases. Therefore, government investment in the program should be a relatively large percentage in the early stages and be increasingly replaced by private capital, especially in the final stages.

The projected DOE portion of program costs, consistent with the schedule goals shown in Figure 7, is tabulated below. Significantly reduced budgets from the level shown could result in major delays and potential increases in the total program costs.

<u>Fiscal Year</u>	<u>Projected Costs</u> <u>\$K 1978 dollars</u>
1977	\$ 1,200*
1978	3,000*
1979	12,000**
1980	16,000
1981	30,000
1982	46,000
1983	54,000
1984	61,000
Program to Completion	318,000

*Actual Costs

**President's Budget

PART II TECHNICAL PLAN

1. OVERVIEW

This part of the plan will describe in detail the technical aspects of the program. The key areas for development will be shown and the program logic and strategy will be discussed. The logic and strategy are planned to bring the molten carbonate fuel cell technology from the Exploratory Development Phase to demonstration and commercialization. The key technology development requirements for the fuel cell and non-cell subsystems are shown in the following section.

1.1 FUEL CELL SUBSYSTEM

Cell and stack development is the primary activity and has the highest priority. There are four aspects to this development (Performance, Cost, and Contaminant Tolerance). The key technical issues for development are defined below for these four aspects of cell development.

Performance

The goal for power density is 127 w/ft^2 at 0.85V. Recently, over 100 A/ft^2 have been achieved in pressurized tests, and the goal of 125 w/ft^2 appears to be well within reach. A higher power density than what has been achieved is desirable because less cell material will be required to produce the same power, thereby, decreasing the cost.

Life

The fuel cell stack goal is 40,000 operating hours between major overhauls (cell replacement under operating conditions). The duration of the longest test run with realistic bench-scale cells was 16,000 hours. This test was terminated by seal corrosion, a problem which appears to have been solved. Presently, the limitation on life appears to be electrolyte loss. This problem

will be solved by either electrolyte storage within the cell or by some provision for periodic replenishment. Another life-limiting phenomenon is gas crossover through the tile, which has been uncovered through more rigorous testing. A sub-goal of 1000 hours of crossover-free operation after 10 thermal cycles has been established as a requisite for subscale stack testing. Approaches to this problem, including selection of electrolyte filler, are underway.

Cell Cost

The important aspects of cell cost, per se, are materials cost and manufacturing cost. Raw material costs appear to be inherently fairly low, but suitable manufacturing methods for the electrolyte tile do not exist as yet. The synthesis of LiAlO_2 has been greatly simplified recently, but hot-pressing, which is a relatively undesirable mass production method, is still utilized. A suitable mass production method is needed by 1983.

Another economic requirement is scale-up. The optimum cell size has not been established, but is most likely greater than the one square foot size of the largest cells operated to date. Subscale (20 cells, 1 ft^2 each) stack tests have been run on clean gases; testing of large, full-scale stacks is expected in 1981.

Contaminant Tolerance

Electrode tolerance to higher sulfur levels is desirable, since anode sulfidation (NiS_x liquid formation) is limiting, but the fundamental problem is sulfur scavenging by the electrolyte from the cathode flow, followed by transport of sulfate to the anode. Corrosion effects of fuel and oxidant streams containing sulfur at the nominal level are not established as yet, nor are other possible contaminant effects. The approach to contaminant evaluation is to use synthesized gas mixtures (1977) followed (1980) by a bench-scale test source using coal, followed (1982) by stack tests on a gasifier.

1.2 NON-CELL SUBSYSTEMS

The development and adaptation of the non-cell subsystems have a further-term priority than the fuel cell subsystem. The development of the non-cell subsystems is only for interface equipment that may be necessary. Issues that will be addressed concerning the non-cell subsystems are described below.

Gasifier

A variety of types of gasifiers appear to be available for use. Preliminary analysis indicates that molten salt, fluidized bed, and entrained flow types are most likely candidates, because of low hydrocarbon and tar output, and simplicity. Molten salt types require less sulfur removal, but may be penalized by complexity and may not be developed in time to meet programmatic needs. Entrained flow types are in an advanced state of development, but it is not clear whether the high sensible heat content of the exit stream is compatible with highest system efficiency. The program logic diagram shown in the next section gives the program schedule for gasifier choice.

Cleanup Subsystems

Recent cell data indicates that sulfur removal to a nominal 1 PPMV level is necessary. There are a variety of low temperature technologies available for cleanup to this level, and cost does not appear prohibitive. High-temperature cleanup is preferred on thermodynamic grounds, but technology development is required, since present high-temperature cleanup cannot remove S to 200 PPMV. A contract is underway to evaluate and, if possible, develop a high-temperature, low-level cleanup process.

Bottoming Subsystems

Although bottoming subsystems are regarded as basically commercially available, some heat exchange technology development may be desirable; this will be defined by systems studies.

Inverter

The DC to AC inverter will be adapted from the phosphoric acid programs.
No major development needs are foreseen.

2. PROGRAM LOGIC

The program is composed of eight activities as was shown in the WBS (Figure 4). The tasks within each activity are a logical aggregation of the work performed under the activity. These tasks are linked to each other within the activity but are also tied to tasks in other activities. This section will describe the interrelationships of the tasks by showing the requirement for the task and the connection with past and/or future tasks. Figure 3 on page 15 showed a simplified logic diagram for the program. Figure 9 is a detailed logic diagram for the complete program which shows the interconnections between the tasks, and Figures 9.1 to 9.6, which are shown in Section 3, are a breakdown of the program into each of the activities.

2.1 FUEL CELL DEVELOPMENT AND STACK SCALEUP

The Molten Carbonate Fuel Cell Program began with an assessment of the technology. The results of the assessment showed that Molten Carbonate Fuel Cells have the potential of being competitive with other advanced power systems, but development of the fuel cell subsystem is required by this program before a fuel cell powerplant would become commercial. The Fuel Cell Development and Stack Scaleup Activity is, therefore, designed to start the development that is required to make the cell subsystem a viable technology.

The individual fuel cell parts are being developed to meet operating goals and parameters. Cell development work to date has been very successful and it appears that the goals for the fuel cell can be met with further development. Because the development achieved to date appears adequate, it is planned to begin the scaleup task before all of the cell work is completed. This will save time, and the coincident development will allow for an appropriate flow of information between the tasks.

Figure 9. Program Logic Diagram

This type of interaction between the tasks is evident throughout the program. Fuel cells are being tested on simulated coal gas, and the data generated by this task is used as input to the cell development task. Individual fuel cells will also be tested with actual coal gas. This coal gas testing will support the Coal Gas Stack Test Activity with information concerning the performance of the fuel cell on coal gas contaminants. The test with cells is required to ensure that the cells will work with coal gas before a large facility is funded for the coal gas stack tests. The information from the cell tests will also be used to develop the reference design by indicating the contaminant tolerance of a fuel cell.

The Coal Gas Stack Test Activity is also supported by the scaleup activities because an operable stack will be required by the test. The stack scaleup tests will also support the Multi-MW Pilot Plant Activity by supplying data on the operation and requirements of fuel cell stacks. This information is required by the Multi-MW Activity in order to design the plant. In order to verify the reliability and performance of the fuel cell subsystem, the subscale stack tests will be used to show long life.

2.2 SYSTEM TRADEOFF AND DESIGN

The technology assessment work showed that the fuel cell powerplant may be a feasible power system, and the fuel cell development work is showing that the fuel cell itself may be able to meet its goals. Detailed technology assessment and system design work should then begin in order to lay the groundwork for the future work that is required for the program.

The System Tradeoff and Design Activity has two main objectives which will assist the process of test and demonstration of the fuel cell technology. Reference designs will be developed for each market application through a succession of design/selection tasks. Gasifier-cleanup subsystems will be

assessed as a separate subsystem due to the developmental nature of gasifier and cleanup technology.

The reference designs are needed as a guide for further development and testing, and will be modified to reflect new data produced by the tests in this program and other new data made available. The subsystems of the updated designs will be verified and the optimized reference design will be the basis of the conceptual design.

The gasifier-cleanup assessments are required as an input to the selection of the reference designs. The coal gas stack test requires that a test site with a gasifier-cleanup subsystem be available. The assessment tasks will assist the test site selection by providing information on the state of development of the subsystems and by estimating the future status of the subsystems.

2.3 COAL GAS STACK TEST

After individual cells are tested with coal gas, the next step is to test stacks of cells on coal gas. If it appears that gasifier-cleanup subsystems can meet the contaminant tolerance established by individual fuel cells, the cells need to be tested in the next higher scale with a full scale gasifier-cleanup system. The requirements for the test will be developed and a site will be selected. This site will already have an operating fuel processing subsystem. This selection will use data collected during the assessments of gasifier-cleanup (Task 2.2 and 2.5). A fuel processing simulator will be operated to assist in the selection by defining the operating ranges and limits of the gasifier-cleanup subsystem for the test. The test will be designed using this information along with data on stack performance generated by the clean gas stack tests (Task 1.4).

The coal gas stack test is undertaken to test the performance of the fuel cell stack with actual coal gas and the interaction of the two subsystems. These tests are required to provide data to verify operation of the fuel cell subsystem before funding the demonstration powerplant.

2.4 MULTI-MW PILOT PLANT

A large-scale (pilot plant) facility is the intermediate step between the fuel cell stack tests on clean and coal gas and the demonstration plant. Only after the successful operation of the fuel cell stack on coal gases will the funds be committed to a Multi-MW facility. The operation of the coal gas stack test will show that the stack can operate on coal gases and the next step for testing is a pilot-scale plant.

The Multi-MW test will utilize the most developed fuel cell design. The manufacturing process for all fuel cell components must be highly developed in order to meet the requirements imposed by the end use application on the fuel cell. The manufacturing capability will be established to produce fuel cells at a volume high enough to support the Multi-MW test. This process should also be compatible with mass production techniques required for the demonstration powerplant. The demonstration powerplant would be the next scaleup after the Multi-MW test. This test will be performed in order to provide the required verification data on the fuel cell subsystem before a demonstration plant is funded. The Multi-MW test should be performed to minimize the risk and ensure the successful operation of the demonstration plant.

2.5 VERIFICATION

This is the last activity before the demonstration powerplant is constructed. All of the design, development and test data is collected and analyzed to ensure that sufficient development and test has been completed before

making a commitment to build a demonstration powerplant. Data on the individual fuel cells along with data on stacks and the Multi-MW test is used to verify the fuel cell performance and reliability. The other subsystems are verified through the use of the reference design and test data from the coal gas stack test. Additional data on the fuel processing subsystem will be gathered and a full-scale gasifier-cleanup subsystem will be operated to simulate fuel cell powerplant conditions if required. The compatibility of all of the subsystems will be established.

The verification of the subsystems and the system as a whole is undertaken to provide data to the design of the demonstration powerplant and to confirm the readiness to proceed with the demonstration powerplant.

2.6 DEMONSTRATION POWERPLANT

A demonstration powerplant is built for each market application in order to show that the Molten Carbonate Fuel Cell powerplant is an economic, environmentally acceptable and efficient method of producing energy from coal. The plant will be operated by a host user and will provide confidence in the market for the commercialization of the fuel cell technology.

The previous activities will have shown that the powerplant can be made operational and will perform according to the requirements and constraints that the user imposes on a power system. This activity starts with the preparation of the conceptual design for the demonstration powerplant. This design defines the system that would be built and is used as the basis for the funding commitment. This design is developed into the final design after a decision is made to proceed with the powerplant. The fuel cell manufacturing capability is established based on the process that was used for the Multi-MW test. Once the powerplant is built and checked out, the operation

is turned over to the host user. The operating data will be used as the basis for the commercialization of the fuel cell technology.

3. STRATEGY

This section of the plan is written to describe in detail the work required by the program. The technology problem areas were identified in the Overview as were the development priorities. The Program logic was presented along with the program logic chart. An in-depth discussion of objectives, status, problem areas, subtasks, and outputs for each of the tasks shown in the WBS (Figure 4) is presented below along with the logic for each of the activities.

3.1 FUEL CELL DEVELOPMENT AND STACK SCALE-UP (Figure 9.1)

This activity has the highest priority since it encompasses the near-term development of the fuel cell and the first steps toward the large-scale testing of the fuel cell stack. To date, the first task of this development has been completed. The program was started with this task (Assess status of technology) and has provided an in-depth understanding of the characteristics and problems of the molten carbonate fuel cell. Studies such as the ECAS study have shown that the molten carbonate fuel cell powerplant has the potential of being a feasible competitive power system.

The flow of the future tasks as shown in the program logic is to develop the individual fuel cell to meet the operating goals for the fuel cell and test the cell on dirty gases and then stack the fuel cells together until a full scale stack has been tested on clean gases.

3.1.1 Cell Development

The objectives of this task is to develop the individual fuel cell to reach the goals for operation and performance and to further develop the fuel cell operation as justified. The operating goals and parameters as presently understood, are shown as follows:

Figure 9.1. Program Logic for Cell Development

Performance: 125 w/ft² @ 0.85V/fuel from coal gasifier-cleanup
Life: 40,000 hours
Cost: \$7-10/ft² (\$1977 dollars)
Operability: Functional under reference design conditions
Cell Scale-Up: > 2ft² surface area

These goals have been established based on design parameters such as 80 percent fuel utilization and the interaction between the performance parameters. In an IGT final status report, 9/30/77, Project 8984, the performance achieved was reported to be 100 w/ft². Life-limiting problems appear to have been solved, and life tests have achieved 16,000 hours (EPRI final report RP114; ANL 77-56, 1/8/77; ANL 78-40, 1/5/78). It appears possible to develop cost-effective manufacturing techniques which will meet the cost goal. Work in progress under EPRI funding (RP114-2) indicates that the operability goal can be met. Cells of 1 ft² size have been tested and cells 2 ft² have been manufactured by GE and ERC.

This cell development task will address problems of electrolyte management by developing a cell structure having adequate electrolyte retention and/or means of replenishment of electrolyte. Anode materials will be tested to increase performance and decrease sintering. Cathode materials will be tested for increased mechanical strength, performance, conductivity, and manufacturability. New intercell materials will be tested to produce good conductivity and control of gas distribution, decrease cost, and ensure that the materials will have adequate mechanical properties.

The inherent cell performance, and operability of the fuel cell design will be verified with respect to resistance, cracking and thermal cycling capability, cost, and life. The cell design can then be used for the stack scale-up tests.

CELL DEVELOPMENT OVERVIEW (WBS 1.1)

OBJECTIVES

- o Develop individual fuel cell to meet operating goals & parameters
- o Further development of fuel cell operation as justified

STATUS

- o Performance achieved 100 w/ft²
- o Life limiting problems have been solved. Achieved 16,000 hrs.
- o Manufacturing techniques can be developed
- o Operability goal can be met
- o Cell scale up appears achievable

KEY PROBLEMS

- o Electrolyte management
- o Manufacturing processes
- o Strength of cell materials

SUBTASKS

- o Develop & test anode, cathode, cell structure and intercell materials

TASK OUTPUTS

- o Verification of cell performance and operability
- o Cell design for stack level tests

3.1.2 Coal Gas Cell Test

In parallel with the Cell Development Task, this task will be undertaken to establish the requirements for the fuel gas imposed by the fuel cell for contaminant level. The cell components will also be developed to a level where the contaminant tolerance of the cell allows acceptable performance degradation on reference design gas. Presently, the contaminant tolerance of molten carbonate fuel cells to sulfur in the feed gas appears to be 1 PPMV, (IGT final status report, Project 8984, 9/30/77; GE Quarterly Programs Report 5/16/78, EC-77-C-03-1479) but the identity and/or effects of other contaminants that may effect the fuel cell have not been quantified. This task will have to identify the deliterious contaminants, quantify the effects of the contaminants

of fuel cells, and then develop cell materials possessing the desirable contaminant resistance. Based on the above, the requirements for the coal gas cleanup can then be specified.

COAL GAS CELL TEST OVERVIEW (WBS 1.2)

OBJECTIVES

- o Establish fuel gas requirements

STATUS

- o Sulfur tolerance of fuel cells appears to be 1 ppmv

KEY PROBLEMS

- o Identity and/or effects of other contaminants has not been quantified

SUBTASKS

- o Identification of deliterious contaminants
- o Quantification of contaminant effects
- o Development of contaminant resistant components

TASK OUTPUTS

- o Requirements imposed by fuel cell on cleanup subsystem
- o Cell materials possessing desirable contaminant tolerance

3.1.3 Subscale Stack Test

This task is an intermediate task between work that is performed on cell level and work performed on a full-size stack level. This process allows for a graduated scale-up of the fuel cell technology in order to identify and solve problems on a small scale, thereby reducing the cost of development. A single stack of 20 - 1 ft² cells have been operated (RP114). Results of this test indicate that performance was maintained but further work was required to address problems of operability. Performance has met the goal levels in single cell work and the rate of technology advancement in cost and endurance and the level of development already achieved indicates that scale-up and

stack work should now proceed. Tests will be performed to identify the probability of problems occurring with gas stream control, manifolding, tolerance accumulation, and differential and transient pressures. Design and test iterations will be performed until a successful subscale stack has been demonstrated to meet all requirements. The successful design will be used as the basis for a full-scale stack.

SUBSCALE STACK TEST OVERVIEW (WBS 1.3)

OBJECTIVES

- o Establish the basis for full-scale stack design

STATUS

- o A subscale stack has been operated
- o Single cells are nearing performance goal levels
- o Cell development achieved indicates that scaleup work should proceed

KEY PROBLEMS

- o Gas stream control
- o Manifolding
- o Tolerance Accumulation
- o Ability to withstand differential and transient pressures

SUBTASKS

- o Design and test until successful subscale stack has been demonstrated

TASK OUTPUTS

- o Design basis for full-scale stack

3.1.4 Clean Gas Stack Test

The objective of this task is to confirm the full scale stack design with respect to performance, operability and reliability. These goals for the stack design are to meet the reference design requirements:

Performance: 125 w/ft² @ 0.85V with simulated coal gas

Operability: Functional under reference design conditions, i.e., pressure 5-10 atm., inlet temp. 600°C, outlet temp. 700°C, CO₂ recycle by burner technology, start up & transient conditions as defined in reference design.

It is anticipated that subscale cell and stack testing will establish readiness of the cell to undergo scaleup by July 1, 1981. Testing will be performed to verify the stack design in the areas of tolerance accumulation, physical support, mechanical and thermal stress, cooling/CO₂ recycle manifolding and fuel distribution between and within the cells, temperature distribution, and control of temperature profile. Design and test iterations will be undertaken until a successful full-scale stack has been accomplished.

CLEAN GAS STACK TEST OVERVIEW (WBS 1.4)

OBJECTIVES

- o Confirmation of full-scale stack design
- o Accumulation of test data

STATUS

- o RFP dated _____ will require subscale cell and stack testing
- o Subscale cell and stack testing will establish readiness of cell to undergo full scaleup by July 1, 1981

KEY PROBLEMS

- o Tolerance accumulation
- o Physical support
- o Mechanical and thermal stress
- o Sealing & manifold design
- o Cooling/CO₂ recycle

SUBTASKS

- o Design and test until successful full-scale stack has been accomplished.

TASK OUTPUTS

- o Confirmation of performance, operability, reliability of fuel cell stack
- o Cost estimate support

3.2 SYSTEM TRADEOFF AND DESIGN (Figure 9.2)

The purpose of this activity is to perform the studies required to determine the system requirements based on various applications and assess the technology status of the fuel cell powerplant. Also, various system configurations will be studied and design and optimization studies will be performed. The specific tasks are discussed below.

3.2.1 Application Requirements

The work performed in this task will define certain requirements that the user will specify when acquiring a powerplant. The requirements will be defined for those market areas in which the molten carbonate fuel cell powerplant is assumed to be commercially available. Estimates of future requirements have been made for site of plant, heat rate, effluent, capital cost, and cost of electricity in the ECAS studies. Further studies are in progress such as the EPRI project RP 239-4 which is being performed by Fluor Corp. These studies indicate that the molten carbonate fuel cell powerplant may be competitive with other advanced technologies. The application requirements study will undertake a more in-depth study to define the future market and establish a set of quantitative requirements which can be used to evaluate possible fuel cell powerplant designs.

APPLICATION REQUIREMENTS OVERVIEW (WBS 2.1)

OBJECTIVES

- o Define potential user requirements

STATUS

- o Some future requirements for powerplants have been estimated
- o Future studies are in progress
- o Molten carbonate fuel cells appear competitive
- o This task required by RFP _____

Figure 9.2. Program Logic for System Tradeoff and Design

KEY PROBLEMS

- o Definition of future market
- o Uncertainty in predicting parameters

SUBTASKS

- o Define user requirements for applicable markets
- o Establish constraints and characteristics of powerplants

TASK OUTPUTS

- o Set of quantitative requirements

3.2.2 Gasifier Readiness Assessment

There are a number of gasifier types that are presently under development. The objective of this task is to assess and identify what types of gasifier will be available when they are required by the Molten Carbonate Fuel Cell Program. EPRI's two alternative designs for molten carbonate fuel cell powerplants and ECAS utilize gasifiers as one of the subsystems. Information will be collected on existing and developmental gasifiers, and the present stage of development and future programs for development will be assessed. This assessment will indicate the readiness of the gasifier types when required and the relative probabilities of development. The assessment will be a basis for the choices for the test gasifier, site, and reference design. A key problem for performing this assessment will be to predict what future development of the gasifiers will be achieved. A preliminary assessment has been preformed by General Electric and is included in the 1978 Quarterly Progress Report (5/15/78, EC 77-0C-03-1479).

GASIFIER READINESS ASSESSMENT OVERVIEW (WBS 2.2)

OBJECTIVES

- o Assess and identify gasifier types that will be available when required

STATUS

- o A preliminary gasifier assessment has been made
- o Fuel cell powerplant designs have used gasifiers
- o This work is required by RFP _____

KEY PROBLEMS

- o Predicting future development of gasifiers

SUBTASKS

- o Collect data on existing & developmental gasifiers
- o Assess stage of development and future programs for development

TASK OUTPUTS

- o Summary of present status of gasifier types
- o Long-term goals and estimated performance of gasifiers
- o Basis of choices for test gasifier site and reference design

3.2.3 Potential System Configurations

This task in conjunction with the Applications Requirements task forms the basis of a systematic approach to studying many possible configurations and finally selecting one reference design for each market application. Studies performed in ECAS and the EPRI project 239-4 are based on one or two designs. The screening process will encounter some difficulty in obtaining sufficient data on fuel processing (gasifier & cleanup) subsystems options. But the ECAS and EPRI studies along with the application requirements will be used as a basis for the screening of fuel cell powerplant configurations to determine potential system configurations which will be studied further.

POTENTIAL SYSTEM CONFIGURATIONS OVERVIEW (WBS 2.3)

OBJECTIVES

- o Define potential candidate system configurations for each application
- o Develop systematic approach for the selection of an optimum design

STATUS

- o System configurations have been designed for previous studies
- o This work is required in RFP _____

KEY PROBLEMS

- o Difficulty of obtaining data on gasifier & cleanup subsystems options

SUBTASKS

- o Identify types and characteristics of subsystems
- o Prepare a matrix of system configurations
- o Screen configurations to determine potential system configurations

TASK OUTPUTS

- o Set of potential system configurations for further study

3.2.4 Candidate System Configuration

The objective of this task is to evaluate the potential system configurations in order to select those systems which would best meet the application requirements. This task is required because the selected candidate systems will be used as the basis for the reference design for each market application. Reference designs have been developed by EPRI and in ECAS and can be used as a guide for selecting the candidate configurations. A lack of detailed information on the fuel processing subsystem will hinder the assessment of the system configurations, but the methodology for screening the system configurations by establishing detailed subsystem requirements and analyzing available performance characteristics for subsystems will help minimize the impact of incomplete data. After the candidate system configurations are selected, the operating and performance characteristics of the overall system and subsystems will be described.

CANDIDATE SYSTEM CONFIGURATION OVERVIEW (WBS 2.4)

OBJECTIVES

- o Evaluation of the potential system configurations
- o Selection of candidate systems which will be the basis for reference designs

STATUS

- o Reference designs have been developed in previous studies
- o This work is required in RFP _____

KEY PROBLEMS

- o Lack of detailed information

SUBTASKS

- o Establish detailed subsystem requirements
- o Establish each potential system configuration
- o Analyze performance characteristics

TASK OUTPUTS

- o Description of candidate system configurations
- o Performance characteristics for the subsystems at each candidate system

3.2.5 Gasifier Type Identification

Task 2.2 assessed the future state of development of gasifier types. The key problem of assessing the advantages and disadvantages of different gasifier types will be addressed in this task through further identification of the gasifier types and their characteristics. Preliminary information on the characteristics of some gasifier types is available in the studies by EPRI, GE, and ECAS. The work performed under this task will also develop selection criteria for gasifier that would be used for the reference designs and the stack tests on coal gases. The assessment of readiness will be analyzed in light of the selection criteria and a type of gasifier will be selected for each application.

GASIFIER TYPE IDENTIFICATION OVERVIEW (WBS 2.5)

OBJECTIVES

- o Identify the gasifier that could be utilized for reference design and coal gas stack test

STATUS

- o Preliminary information on gasifier types is available in previous studies
- o This work is required by RFP _____

KEY PROBLEMS

- o Assessing advantages and disadvantages of different gasifier types

SUBTASKS

- o Identify the gasifier types and their characteristics
- o Identify the criteria for selection of a gasifier
- o Selection of gasifier for designs and test

TASK OUTPUTS

- o Set of criteria
- o Ranking of gasifier types
- o Selection of which types could be used for designs and test

3.2.6 Reference Design Selection

A reference design will be established for each of the market applications that will be defined during the Application Requirements Task. The reference designs developed by EPRI and in ECAS will be used as a baseline for a systematic approach to develop a reference design for this task. The number of configurations which were under consideration has been continuously decreased until there remains a single reference design for each application. The reference designs will be used as a tool for establishing requirements for each subsystem, for guiding subsystem research and development, and for defining the interactions among the subsystems. Since subsystem data is still limited, it may be difficult to choose the best reference designs from the candidate designs. Also, it may become a problem to be able to retain flexibility

to modify the designs based on further data assessment. These problems can be alleviated through the selection and optimization process that the program will be undertaking. The criteria for the selection of the reference designs will be established. The candidate systems will then be screened and the reference designs will be chosen. Also, dynamic interaction computer models will be developed, which will allow re-evaluation and modification of the reference designs during future tasks.

REFERENCE DESIGN SELECTION OVERVIEW (WBS 2.6)

OBJECTIVES

- o Establish a reference design for each application

STATUS

- o Reference designs were developed by EPRI and ECAS

KEY PROBLEMS

- o More than one candidate design may be applicable to the market application
- o Choosing a reference design from candidate designs with limited data
- o Retain flexibility to modify design

SUBTASKS

- o Establish criteria for selection of reference design
- o Screen the candidate systems with the criteria
- o Select reference designs
- o Develop dynamic interaction models

TASK OUTPUTS

- o Reference design for each market application
- o Set of requirements for each subsystem
- o Technical development required for each subsystem

3.2.7 System Optimization

Identification of subsystems will begin in 1979 with the selection of the reference design. Full-scale stack tests will begin in 1981. This task will modify the reference designs in order to optimize the system. The optimized

reference designs will be the basis for the demonstration powerplant conceptual design for each market application. Reference designs will have been systematically developed using established system and subsystem requirements. The key problem to be addressed during this task is the system effects of the range of operating conditions for each subsystem including off-design conditions. This problem will be solved through the definition of interface operating conditions and requirements for each subsystem. This will be made possible by test results which will be available from the full-scale stack tests, coal gas stack tests, and the Multi-MW test. These tests will also produce data which will allow the modification of the reference designs. This optimization procedure will enable the system requirements to be periodically updated and required technical development to be further defined.

SYSTEM OPTIMIZATION OVERVIEW (WBS 2.7)

OBJECTIVES

- o Define subsystem interfaces of each reference design
- o Optimize systems

STATUS

- o Identification of subsystems begin in 1979
- o Full-scale stack tests begin in 1981
- o Reference design will be ready to be modified
- o Interface data will have been well defined

KEY PROBLEMS

- o Effects of the range of operating conditions on the system

SUBTASKS

- o Define interface operating conditons
- o Define interface requirements
- o Optimize and modify reference designs
- o Periodic updates of system requirements and required technical development

TASK OUTPUTS

- o Optimal system requirements
- o Basis for conceptual design for each demonstration plant

3.3 COAL GAS STACK TESTS (Figure 9.3)

The first two activities discussed above are concerned with the development and scale-up of the fuel cell and stack, and the development of a design for the fuel cell powerplant. Work performed in the cell development and design activities will support the tasks that will be performed on the Coal Gas Stack Test Activity.

The Cell Development Activity will test cells on coal gases. This activity is required in order to develop acceptable contaminant tolerance on a cell scale in a cost-effective manner. Before the stack test with coal gas is started, the cell should be developed to a state where it can perform with gas that is supplied from a gasifier-cleanup subsystem.

Full-scale stacks will be developed in subscale in order to solve problems in small-scale. Full-scale stack tests will be undertaken to verify the operability and performance of the stack. An operable fuel cell stack is required as is a cell which will tolerate the coal gas contaminants before the coal gas stack test is started.

The System Tradeoff and Design Activity will support the gasifier-cleanup subsystem selection process that is required before that subsystem is located for the coal gas stack test. During the System Tradeoff and Design Activity, the gasifiers and cleanup systems will be assessed as to their state of development and possible future development. The applicability to the fuel cell powerplant configuration will also be assessed, and the type of gasifier-cleanup subsystem will be selected. This work will be used as a basis for

Figure 9.3. Program Logic for Coal Gas Stack Test.

further analysis for the gasifier-cleanup subsystem which will be used for the coal gas stack test. The specific tasks of the Coal Gas Stack Test Activity are discussed below.

3.3.1 Gasifier-Cleanup Requirements and Site Assessment

Before the stack test with coal gases is started, assessment of potential sites should be performed. At the time that the test is to be performed, various gasifier-cleanup subsystems should have already been constructed and in operation for either development or commercial use. These sites will be assessed for fuel cell stack tests on coal gas by considering availability and technical requirements of the gasifier-cleanup subsystem. Since the operation of the test will begin 1982, this assessment shall consider not only existing fuel processing subsystems (gasifier-cleanup pair) but also the plans for development and construction of future fuel processing subsystems. Some of the gasifiers that are presently available and/or under development are Texaco, Lurgi, Westinghouse, and Koppers/Totzek. Cleanup systems such as Stretford, Selixol, and Rectisol are available or are under development.

The key problem to be solved by this task is the screening of gasifier-cleanup sites that will be both available and representative of likely technology. It is planned that the identification of potential requirements of a gasifier-cleanup subsystem along with the determination of the status and availability of the fuel processing subsystems will enable the screening to be made. After the assessment of the sites' ability to satisfy the requirements, a summary of candidate test sites which have the potential of fulfilling the test requirements will be produced.

GASIFIER-CLEANUP REQUIREMENTS AND SITE ASSESSMENT OVERVIEW (WBS 3.1)

Objectives

- o Assess potential gasifier sites for fuel cell stack tests

Status

- o Gasifiers and cleanup systems are commercially available or are under development
- o This work is required in RFP _____

Key Problems

- o Choosing a gasifier-cleanup site that is available and representative of likely technology

Subtasks

- o Identify potential requirements of gasifier-subsystem
- o Determine status and availability of existing and other gasifiers and cleanup subsystems under development.

Task Outputs

- o Definition of requirements for acceptable site
- o Assessment of sites to satisfy requirements
- o Summary of candidate test sites for coal gas stack tests

3.3.2 Gasifier-Cleanup Simulator

Operating ranges and limits for the gasifier-cleanup subsystem will be defined prior to the coal gas stack test. This is required in order to specify the tests that will be performed and will ensure a thorough test on the fuel cell stack and the gasifier-cleanup subsystem. The identification and quantification of deleterious contaminants is being performed in the Cell Development Activity. This work is being undertaken to define the effects mainly on the fuel cell subsystem. These effects need to be defined for the fuel processing and the fuel cell subsystems in an integrated fashion. This work can be done by the gasifier-cleanup simulator.

Fuel cells are currently being tested on synthetic bottle gas mixtures to simulate known major gas contaminants. These tests are being performed by IGT and GE on EPRI and DOE contracts, and at UTC on an EPRI contract. Based on the data from these tests, the fuel cell stack input requirements in terms of contaminant tolerance can be determined. In addition to contaminant requirements, the operating parameters of the fuel cell stack will be estimated to specify the output requirements for the cleanup subsystem. Gasifier-cleanup parameters will be determined to establish the simulator design. Because this simulator will be completed before a specific gasifier-cleanup subsystem will be selected, the simulator design will be required to be able to adequately simulate gas streams from alternate gasifier-cleanup concepts.

During the operation of the simulator, incompatibilities may indicate that modification of fuel cell components may be required. Simulator testing will be performed by more than one contractor. This testing should be performed such that the tests will not be duplicated while ensuring that all contractors will be able to sufficiently exercise their simulators and acquire adequate information to perform the coal gas stack test.

GASIFIER-CLEANUP SIMULATOR OVERVIEW (WBS 3.2)

Objectives

- o Define operating ranges and limits of gasifier-cleanup subsystem for the coal gas stack test
- o Identify problem contaminants and quantify the effect of those contaminants

Status

- o Fuel cells are currently being tested as synthetic bottle gas

Key Problems

- o Design a gasifier-cleanup simulator that will adequately simulate gas stream from alternate subsystem concepts
- o Avoid duplication of test while maintaining contractor capability

Subtasks

- o Determine fuel cell stack input requirements and determine gasifier-cleanup parameters to establish simulator design
- o Design and build simulator
- o Simulate gasifier operation
- o Modify fuel cell components as needed
- o Identify requirements on cleanup subsystem output

Task Outputs

- o Improved cell components
- o Set of requirements on cleanup subsystem

3.3.3 Coal Gas Stack Test Site Selection

Prior to the beginning of this task, the requirements and availability of sites will have been determined by the Gasifier-Cleanup Requirements and Site Assessment Task. The candidate test sites will be screened to select an acceptable site(s) for testing fuel cell stacks with fuel gas from a coal gasifier-cleanup subsystem. This site selection task is required in order to assure the best possible matching of the output of the fuel processing subsystem to the input requirements of the fuel cell stack. The selection procedure will include the establishment of technical requirements for the site(s) and the establishment of evaluation criteria for the selection of the site(s). An acceptable site(s) that will fulfill the requirement and criteria for a test of the fuel cell stack on coal gas will then be chosen. This task is included in the RFP.

COAL GAS TEST SITE SELECTION OVERVIEW (WBS 3.3)

Objectives

- o Select acceptable site(s) for testing fuel cell stacks with fuel gas from a coal gasifier-cleanup subsystem

Status

- o Requirements and availability of sites is determined in Task 3.2
- o This task is required by RFP _____

Key Problems

- o Choosing the site which best satisfies stack test requirements

Subtasks

- o Establish technical requirements for the site
- o Establish evaluation criteria for selection of the site
- o Select site(s) best suited for the test

Task Outputs

- o Acceptable site(s) that will fulfill requirements and criteria for the coal gas stack test

3.3.4 Coal Gas Stack Test

This test will generate data on the fuels processing subsystem, the fuel cell subsystem operating on coal gases and the interactions between the two subsystems. The test data will be used for the verification of the fuels processing subsystems and the fuel cell reliability. The data will also be used to establish the performance of the fuel cell. This test will also establish the compability between the fuel cell stack and the gasifier-cleanup subsystem. Prior to this test, coal gas will have been used only on a single fuel cell scale with stacks being tested only on clean gases. This test will represent a major step in the integration of the two subsystems.

The operating range and limits of a gasifier-cleanup subsystem will have been simulated and the technical requirements for the test will have been established in previous tasks. The operating range for each subsystem will

have to be defined for the purposes of the test. This will be accomplished by establishing test requirements and testing various operating conditions. This test data will be evaluated and the test hardware will be modified if necessary for further testing.

COAL GAS STACK TEST OVERVIEW (WBS 3.4)

Objectives

- o Establish compatibility between fuel cell stack and gasifier-cleaner subsystem

Status

- o Individual cells are being tested on simulated coal gas
- o Full-scale stacks are tested in Task 1.4 on clean gas
- o Operating range and limits of a gasifier-cleanup subsystem are simulated in Task 3.2
- o Technical requirements of the test site are established in Task 3.3

Key Problems

- o Integration of the subsystems
- o Definition of operating range for each subsystem for the purposes of the test

Subtasks

- o Establish test requirements
- o Design subsystem interfaces
- o Design and build test hardware
- o Test various gases in the stack
- o Test various operating conditions
- o Evaluate results and modified test hardware

Task Outputs

- o Test data on the fuel cell stack and interactions between subsystems

3.4 MULTI-MW TEST FACILITY (Figure 9.4)

This activity represents one further step of the systematic approach to developing a feasible molten carbonate fuel cell powerplant. Cells were

Figure 9.4. Program Logic for Multi-MW Pilot Plant

developed and scaled up into stacks of cells. The system was designed and modified. The fuel cell stack will have been tested on design coal gas and the fuel cell stack is to be tested in a pilot plant-size facility. This facility will be the last major test before a demonstration plant is constructed. The operating data from this facility will form part of the basis for making the go/no go/delay⁺ decision on a demonstration powerplant.

3.4.1 Manufacturing Process for Multi-MW Test

A manufacturing technique exists for all fuel cell components today, but the technique in widespread use for electrolyte tile production is not suitable for mass manufacture. Suitable techniques for tile manufacture are under development at IGT under DOE contract (project 8984). Processes are being developed at ANL and they appear attractive.

Once suitable manufacturing processes are established, manufacturing capability for fuel cell components must be established. This manufacturing capability will be at a level which will support Multi-MW testing. The process which will be established must be adaptable to the mass production rates necessary for the Multi-MW test and be eventually capable of being used in a manufacturing line that will be needed for the demonstration powerplant. In order to verify that the components will meet specifications when produced under these mass production techniques, the impact of the manufacturing process design and/or performance of the fuel cell will be evaluated.

MANUFACTURING PROCESS FOR MULTI-MW TEST OVERVIEW (WBS 4.1)

Objectives

- o Establish a manufacturing process for all fuel cell components
- o Provide manufacturing capability for fuel cell components for Multi-MW testing

Status

- o Manufacturing technique exists for all components
- o Electrolyte tile process is under development due to inadequacy of present process
- o This task is required by RFP _____

Key Problems

- o The present tile process is not suitable to mass production
- o Develop a high volume process to produce cells which are economic and have high performance

Subtasks

- o Identify practical manufacturing techniques
- o Identify critical components which are difficult to manufacture and or assemble
- o Evaluate impact of manufacturing process on design and/or performance
- o Construct a manufacturing line for the Multi-MW test
- o Verify that components meet specifications

Task Outputs

- o Process for the manufacture of fuel cell components which can meet volume requirements for Multi-MW test and demonstration
- o Manufacturing capability to produce fuel cell components for the Multi-MW test

3.4.2 Multi-MW Pilot Plant

Large-scale testing of the fuel cell powerplant should be undertaken before a demonstrator is started. A large-scale plant provides performance data for the integrated system that is not produceable in a small-scale test. The Multi-MW pilot plant will test the integration of all subsystems to ensure that they function according to design when operated as an integrated system. Also, with a pilot-scale system, operation experience can be gained and reliability and performance data can be collected.

At present, cell development and testing is progressing toward a fuel cell which meets operating goals. Stack testing and scale up have started and will be completed in 1981. This will allow sufficient time for developing the manufacturing process and capability required for the pilot plant which will start testing in 1984. The conceptual and detailed design for the Multi-MW Pilot Plant will integrate the powerplant using the best available support subsystems. After the powerplant is built, it will be tested and checked out. Based on the checkout, integration hardware will be modified or developed as needed.

MULTI-MW PILOT PLANT OVERVIEW (WBS 4.2)

Objectives

- o Test the integration of all subsystems within the system to ensure that they function according to design
- o Increase experience with pilot scale system to collect reliability and performance data

Status

- o Cell development and testing is progressing toward a fuel cell which meets the operating goals (Task 1.1)
- o Stack testing and scaleup have started and will be completed in 1981
- o Manufacturing process and capability is established in Task 4.1

Key Problems

- o Integration of fuel cell powerplant of significant scale using best available support subsystems

Subtasks

- o Determine facility requirements by conceptual design
- o Acquire funding
- o Locate site for test
- o Prepare Environmental Impact Statement
- o Design and build facility
- o Test powerplant
- o Checkout
- o Modify and develop hardware

Task Outputs

- o Data on interactions at the subsystems
- o Typical data on fuel cell behavior (performance and reliability) and fuel cell uniformity

3.5 VERIFICATION (Figure 9.5)

This activity is designed to take all of the test data generated in the prior activities and verify that the modified reference design can be developed into an operable and reliable system that will perform according to established goals. Each of the subsystems is to be verified and the compatibility of the subsystems will be established. This activity will ensure that adequate data is available on the operation of each of the subsystems in order to be able to perform the verification analyses. If the data is insufficient, further testing will be undertaken on test equipment such as the coal gas stack test facility or the Multi-MW Pilot Plant. Testing of well documented subsystems such as the bottoming and power processing subsystems could be performed by testing an existing test or demonstration facility or a commercial plant. This testing would be performed by operating the facility or plant under conditions that might be experienced when the subsystem is part of a fuel cell power plant.

3.5.1 Full-Scale Gasifier-Cleanup Subsystem

At present, there are a number of gasifier and cleanup subsystems which are in commercial use or are under development. None of those subsystems

Figure 9.5. Program Logic for Verification

has been operated for the purpose of simulating a fuel processing subsystem in full-scale molten carbonate fuel cell powerplant. The purpose of this task is to ensure that sufficient test or operating data is available for the verification of the fuel processing subsystem.

Because many fuel processing systems are in operation or under development, the test and operating data of these systems may be applicable to a fuel cell powerplant. In order to make that determination, the fuel processing system operating experience must be evaluated to ensure that adequate testing and/or operation under conditions simulating fuel cell operation has been conducted. Data on gasifier development funded by DOE is reported in the "Coal Gasification" quarterly reports issued by the Division of Coal Conversion. If it is found that there is not sufficient applicable data required for the verification of the fuel processing subsystem, tests will be initiated to supply that data.

FULL-SCALE GASIFIER-CLEANUP SUBSYSTEM OVERVIEW (WBS 5.1)

Objectives

- o Verify that a gasifier-cleanup system has been operated
- o Verify that sufficient experience has been accumulated with the gasifier-cleanup subsystem to warrant building a demonstration system using that gasifier-cleanup subsystem.

Status

- o Several gasifier and cleanup subsystems have been operated in commercial service
- o Other gasifier and cleanup subsystems are in advanced state of development

Key Problems

- o Ensure that gasifier and cleanup experience is relevant to fuel cell application

Subtasks

- o Evaluate gasifier and cleanup operating experience
- o Ensure that tests relevant to fuel cells have been performed
- o Incorporate test results in reference design activity

Task Outputs

- o Verification of operating characteristics of the gasifier-cleanup subsystem to be used in demonstration powerplant

3.5.2 Fuels Processing Subsystem Verification

In task 5.1 above, the operating and test data required for this task will have been collected, and additional testing of the fuel cell stack on coal gas will have been undertaken. Also, simulation models will have been developed during the System Tradeoff and Design Activity. One such model was developed by Physical Sciences, Inc. under DOE contract EY-76-C-03-1254. During this task the operating requirements for the fuels processing subsystem will be established. The simulation models will be tested in order to determine the operating characteristics of the fuels processing subsystem with changes in design and system operating conditions. These tests along with the actual operating and test data will become the basis of the verification of the quality of outputs from the fuels processing subsystem and the interaction with the fuel cell subsystem for use in the conceptual design.

FUELS PROCESSING SUBSYSTEM VERIFICATION OVERVIEW (WBS 5.2)

Objectives

- o Verify the operating characteristics of the fuels processing subsystem for use in the conceptual design

Status

- o Tests are performed on a large scale gasifier-cleanup subsystem if required in Task 5.1
- o Tests are performed on full-size study with coal gas from a gasifier-cleanup subsystem in Task 3.4

Key Problems

- o Determine operating characteristics of this subsystem with changes in design and operating conditions
- o Determine from data gathered by the full-scale gasifier and the coal gas stack tests, the verification of the fuels processing subsystem

Subtasks

- o Establish operating requirements
- o Test simulation models
- o Verification of subsystem

Task Outputs

- o Verification of the quality of outputs from fuels processing subsystem and the interaction with the fuel cell subsystem for use in conceptual design

3.5.3 Power Processing Subsystem Verification

The characteristics of power processing systems are well known but it appears that further testing of a power processing subsystem will be required. This testing will be performed on the first generation 4.8 MW demonstration powerplant in order to verify the operation of the subsystem within that powerplant. An equivalent subsystem has been successfully applied to the first generation 1-MW fuel cell plant. Performance and cost have been shown to be acceptable.

Before the testing on the 4.8 MW demonstrator is started, the configuration of the power processing subsystem will be defined for the molten carbonate fuel cell powerplant. The operating requirements will be established, and the data generated by the test will form the basis for the verification of the power processing subsystem for use in the conceptual design.

POWER PROCESSING SUBSYSTEM VERIFICATION OVERVIEW (WBS 5.3)

Objectives

- o Test a power processing subsystem to verify the operation of the subsystem within a fuel cell powerplant demonstration
- o Verify that the operating characteristics of the power processing subsystem are compatible with the fuel cell powerplant design

Status

- o An equivalent subsystem has been successfully applied to the first generation 1-MW fuel cell testing
- o A similar power processing subsystem is being applied to the 4.8 MW demonstration of the first generation fuel cells
- o Performance and cost are acceptable

Key Problems

- o Configuration of the fuel cell and power processing subsystems. Cost vs. performance tradeoffs.

Subtasks

- o Define configuration
- o Establish operating requirements
- o Test under simulated conditions
- o Verification by test

Task Outputs

- o Matrix of operating characteristics of the power processing subsystem to verify the subsystem for use in a fuel cell powerplant demonstration
- o Verification of the power processing subsystem for use in the conceptual design

3.5.4 Bottoming and/or Heat Supply Subsystem Verification

There are a large number of bottoming and heat supply systems in commercial operation. The operating characteristics of these systems are very well known due to the fact that these systems are very common and have been in operation for a long time. These systems have not been used as part of a molten carbonate fuel cell powerplant and the interactions between a bottoming and/or heat

supply subsystem and the rest of the subsystems in a molten carbonate fuel cell powerplant have not been analyzed in detail.

This task is required to perform this analysis in order to verify that a bottoming and/or heat supply subsystem is compatible with fuel cell powerplant design. A set of requirements for the bottoming and/or heat supply subsystem will be established. The available data on the subsystems will be analyzed and it will be determined if any of the subsystems of the powerplant will require modification. Finally, a bottoming and/or heat supply subsystem will be recommended for each end use application.

BOTTOMING AND/OR HEAT SUPPLY SUBSYSTEM VERIFICATION OVERVIEW (WBS 5.4)

Objectives

- o Verify that a bottoming and/or heat supply subsystem is compatible with fuel cell powerplant design

Status

- o A significant amount of data exists on the operating characteristics of this subsystem

Key Problems

- o Determine if modification to subsystems is required

Subtasks

- o Establish a set of requirements for the bottoming or heat supply subsystem
- o Analyze available data on bottoming and heat supply subsystems
- o Determine design changes
- o Test if required

Task Outputs

- o Matrix of operating characteristics of the bottoming subsystem to verify the subsystem for use in a fuel cell powerplant demonstration
- o Recommended bottoming or heat supply subsystem for each end use application

3.5.5 Compatibility Establishment

All of the subsystems will have been or will be completing the process of being verified. This task is required in order to verify the compatibility of those subsystems and to show that the system will remain stable under transient conditions. This task will be accomplished through computer modeling of the system and the testing and exercising of these models. Simulation code will have been developed when the first reference design was completed. Flow simulator models will be developed and exercised during this task. The information derived from the exercising of these models will be used for both the verification of the system and the development of the conceptual designs in a future task.

COMPATIBILITY ESTABLISHMENT OVERVIEW (WBS 5.5)

Objectives

- o Ensure compatibility of subsystems that will be used for the conceptual design of the demonstration powerplants

Status

- o All subsystems are verified in Tasks 5.2, 5.3, 5.4, 5.7
- o Simulation code will exist from Task 2.6

Key Problems

- o System stability under transient conditions

Subtasks

- o Construct flow simulator models as required
- o Experimentally verify powerplant simulation code as required
- o Exercise system simulator code
- o Modify specifications as required
- o Conduct simulation analysis and test as required

Task Outputs

- o Verification of compatibility of the subsystems for the conceptual design of the demonstration powerplants

3.5.6 Fuel Cell Performance

Performance data on fuel cells are being and will be generated by test. At present, tests are being performed on fuel cells with simulated coal gas. Subscale stack tests, coal gas stack tests, and Multi-MW Pilot Plant tests will be undertaken which will produce performance data.

These data will be evaluated to estimate the performance of the fuel cell in an integrated system and to verify that acceptable fuel cell performance has been demonstrated. In this manner the performance and operability of the fuel cell subsystem can be verified. Also, the reliability will be statistically estimated and, except for reliability, this task will establish the basis for completing the conceptual design.

FUEL CELL PERFORMANCE OVERVIEW (WBS 5.6)

Objectives

- o Establish performance of fuel cell subsystem
- o Show that fuel cell design meets performance goals
- o Statistically define reliability and operability of fuel cell subsystems
- o Establish basis for proceeding with conceptual design except for life

Status

- o Tests are presently being performed on fuel cells with simulated coal gas (Task 1.2)
- o Fuel cell stacks are tested on a pilot plant-scale (Task 4.2)
- o Fuel cell stack is tested with coal gas (Task 3.4)

Key Problems

- o Correlation of test data to estimate performance of the fuel cell in an integrated system
- o Performance and operability of the fuel cell in an integrated system

Subtasks

- o Evaluate test data from the Multi-MW test and the coal gas stack test
- o Application of data to conceptual design of each demonstration plant

Task Outputs

- o Verification of performance operability of fuel cell subsystem
- o Verification of powerplant integration
- o Confirmation of readiness to proceed with conceptual design of each demonstration powerplant

3.5.7 Fuel Cell Reliability Verification

Tests are being performed on individual fuel cells to improve life. To date, life of 16,000 hours has been achieved. Tests will be performed with coal gases and at a Multi-MW scale, and long-term subscale verification of fuel cells will be completed. The present accomplishment and these future tests will be the basis for the verification of the reliability of the fuel cell system. The test data will be evaluated to estimate the reliability that can be expected of the fuel cell subsystem when installed in either an industrial cogeneration or baseload system and to determine if the fuel cell subsystem design will meet the life goal of 40,000 hours. This evaluation will also show if the fuel cell subsystem reliability is adequate to warrant design and construction of the demonstration powerplant.

FUEL CELL RELIABILITY VERIFICATION OVERVIEW (WBS 5.7)

Objectives

- o Verify reliability of fuel cell subsystem
- o Show that fuel cell subsystem design will meet life goal of 40,000 hours

Status

- o Tests are being performed on individual fuel cells to improve life (Task 1.1)
- o Life of 16,000 hours has been achieved
- o Tests will be performed with coal gases (Task 3.4) and a Multi-MW scale (Task 4.2)
- o Long-term subscale verification of fuel cells will be completed (Task 5.6)

Key Problems

- o Life tests are very long tests
- o Verification of reliability based on results from different tests

Subtasks

- o Collect test data from the fuel cell development tests, long term subscale fuel cell testing, the Multi-MW test, and the stack level test on clean and coal gas
- o Evaluate this test data to determine if the fuel cell subsystem reliability is adequate to warrant design and construction of demonstration powerplant

Task Outputs

- o Estimation of reliability that can be expected of the fuel cell subsystem when installed in either a baseload or cogeneration system
- o Verification of capability to meet goals

3.6 DEMONSTRATION POWERPLANT (Figure 9.6)

The goal of the development, testing, and verification of the subsystems of the Molten Carbonate Fuel Cell powerplant was to show that a full-scale commercial-size fuel cell powerplant can be demonstrated to be a technically feasible, cost-effective method of producing power from coal. The tasks under this activity will utilize the information produced during the development, testing, and verification to complete the conceptual and final design. The verification activity will produce data which will be used to make the go/no go/delay decision on the construction of the powerplant. After the demonstration powerplant has been operated by the end user, an activity to promote the commercialization of the molten carbonate fuel cell powerplant will be undertaken.

3.6.1 Complete Conceptual Design of Demonstration Plant

In order to make the go/no go/delay decision, the demonstrator will require a conceptual design of the whole system. Prior to the completion of the conceptual design, the reference design (Task 2.7) will have been modified and updated and all verification tests (Tasks 5.2-5.7) have been or will

Figure 9.6. Program Logic for Demonstration Power Plant

be shortly completed. System compatibility will have been established. In order to complete this task, the design and test data will be collected and a site-specific conceptual design will be prepared for each demonstration plant.

COMPLETE CONCEPTUAL DESIGN OF DEMONSTRATION PLANT OVERVIEW (WBS 6.1)

Objectives

- o Finalize the conceptual design for each market application
- o Use the completed design as a basis for the decision to proceed with the demonstration plant

Status

- o Reference design will have matured (Task 2.7)
- o All verification tests will have been or will be shortly completed
- o System compatibility will have been established

Key Problems

- o Adaptation of design to specific demonstrator site

Subtasks

- o Collect design and test data
- o Prepare site-specific design

Task Outputs

- o Conceptual design for each demonstration plant

3.6.2 Powerplant Commitment

This task will prepare all of the information required to make a decision on the construction of the demonstration powerplant. An assessment of the technology will be made using the conceptual design and data showing that the fuel cell subsystem will meet reliability goals. The estimates of natural benefits received by implementing the fuel cell technology will be assessed. The demonstrator will be used in an end use application of commercial size. A user will be identified and a site will be selected. Also, the amount

of user participation will be determined for the design and construction of the powerplant. Management plans and draft environmental impact statements will be prepared. RFPs will be prepared for the design and construction work that will be required to put the plant into operation.

POWERPLANT COMMITMENT OVERVIEW (WBS 6.2)

Objectives

- o Make go/no go/delay decision with construction of demonstration powerplant based on conceptual design

Status

- o Conceptual design, and estimates of national benefits will have been completed
- o Fuel cell reliability information will have been generated

Key Problems

- o Assessing the benefits and technology status
- o Defining user participation in demonstration

Subtasks

- o Assess technology status
- o Assess benefits
- o Identify host user and identify site
- o Prepare management plans
- o Prepare draft environmental impact statements

Task Outputs

- o RFPs for A&E's services
- o Program plans for the demonstration powerplant
- o Site selection

3.6.3 Manufacturing Capability for Demonstration Powerplant

The Multi-MW facility requires that a process be developed for the manufacturing of all fuel cell components. This process is to be adaptable for the production of the fuel cells on a scale required for the Multi-MW test and for the mass production required by the demonstration plant. Design changes for the fuel cell may be required in order to enable the manufacturing

equipment to produce fuel cells in sufficient quantity required for the demonstration and meet cost goals. Manufacturing procedures will be established and manufacturing hardware will be required. If any fuel cell design changes are required, the changes will be assessed to ensure that an acceptable fuel cell design is produced.

MANUFACTURING CAPABILITY DEMONSTRATION POWERPLANT OVERVIEW (WBS 6.3)

Objectives

- o Establish manufacturing capability which will be able to produce sufficient fuel cells for a full-size demonstration powerplant

Status

- o Manufacturing process will have been established for the Multi-MW test (Task 4.1)
- o Manufacturing capability for the Multi-MW test will have been progressively developed through multi-phase demonstrations

Key Problems

- o Increased volume of manufacturing process, small changes in fuel cell design to accommodate scale-up process, meet cost goals

Subtasks

- o Establish manufacturing procedures
- o Acquire manufacturing hardware
- o Assess fuel cell design changes

Task Outputs

- o Fuel cell production capability
- o Acceptable fuel cell design

3.6.4 Complete Drawings

The conceptual design will be used as the basis for the detailed design of the demonstration powerplant. The site will have been selected and final drawings can be drawn which will be the basis for proceeding with construction. Care will have to be taken when scaling up the subsystems and designing

integration components. This work will be accomplished by letting a contract to an architect-engineer firm which will prepare the final design and manufacturing drawings.

COMPLETE DRAWINGS OVERVIEW (WBS 6.4)

Objectives

- o Based on conceptual design, provide basis for proceeding with construction

Status

- o Conceptual design and all test data will have been completed (Task 6.1)
- o Site will have been selected (Task 6.2)

Key Problems

- o Physical integration and location of plant components
- o Scaleup of subsystems

Subtasks

- o Let contract to A&E
- o Prepare final design
- o Prepare manufacturing drawings

Task Outputs

- o All drawings and specifications required for construction

3.6.5 Construction and Checkout of Demonstration Powerplant for Initial Application

This task completes the DOE involvement in the development and demonstration of the Molten Carbonate Fuel Cell Powerplant. All design and drafting will have been completed and the fuel cell manufacturing capability will have been established. The powerplant will be constructed on a site that has been agreed to by the user. The construction will be contracted and monitored to ensure that the construction specifications are being met. After construction has been completed and the plant accepted, it will be checked out. Operation of the demonstration powerplant will then be taken over by

the user. Operating data will be used as the basis for the verification of the benefits of the total system and establish operating characteristics. If the operating data is favorable, a commercialization program will then be undertaken.

CONSTRUCTION AND CHECKOUT OF DEMONSTRATION POWERPLANT FOR INITIAL APPLICATION OVERVIEW (WBS 6.5)

Objectives

- o Build a powerplant to demonstration operation
- o Verify benefits of the total system

Status

- o All design and drafting has been completed (Task 6.4)
- o Fuel cell manufacturing capability has been also established (Task 6.3)

Key Problems

- o Ensure construction to meet specification
- o Achieve operation

Subtasks

- o Contract construction
- o Monitor construction
- o Accept completed plant
- o Checkout

Task Outputs

- o A demonstration powerplant ready for operation by user

3.7 Demonstration Powerplant

The WBS elements 7.1 through 7.5 are similar to WBS 6.1 through 6.5 which were described in the previous section. Also, the logic of the two demonstration plants is the same except that the plants have different market applications and therefore different bottoming systems. The baseload powerplant would generally utilize a steam or gas turbine generator; whereas, the industrial cogeneration powerplant would use the fuel cell waste heat for process heat

or other heat supply subsystems. The differences in the scheduling of these two demonstration plants are shown in the next section - Program Schedule.

4. PROGRAM SCHEDULE

The DOE program to develop a molten carbonate fuel cell power plant began in January 1976. It was started with a task to assess the status of molten carbonate fuel cell technology. Based on the favorable outcome of the assessment, work was undertaken to develop and test the fuel cell. This work has been successful in increasing the performance and reliability of the cell. An RFP has been issued and the work requested by the RFP would continue the cell development and expand the program through the starting of the tasks below. The schedule for these tasks and the remainder of the program is shown in Figure 10.

- 1.3 Test Subscale Stacks
- 2.1 Determine Application Requirements
- 2.2 Assess Gasifier Readiness
- 2.3 Determine Potential System Configurations
- 2.4 Select Candidate System Configuration
- 2.5 Identify Gasifier Type
- 2.6 Select Reference Design
- 3.1 Assess Gasifier Cleanup Requirements and Available Sites
- 3.2 Operate Gasifier Simulator
- 3.3 Select Coal Gas Test Site

The next major contract which appears as a major milestone in the Program Schedule Diagram is the Coal Gas Stack Test which is followed by the Multi-MW pilot plant, the cogeneration demonstration, and the baseload demonstration.

Each of the tasks shown in Figure 10 must be met on schedule by at least one contractor in order to fulfill program needs. However, it is not necessary that all major contractors meet all the schedule points in the period before 1982 since there is considerable diversity of experience and capability among the major contractors at present.

Figure 10. Program Schedule Program

APPENDIX A

Description of MCFC technology

Figure A-1 is a conceptualized drawing of one repeating element in a stack of molten carbonate fuel cells. Fuel enters the cell in a plane parallel to the anode and reacts at the anode-electrolyte interface. The CO in the fuel can react as shown in the anode reaction, but a more favored path is via conversion to hydrogen by the shift reaction

followed by consumption of the hydrogen. The shift reaction is rapid at cell temperature in the presence of the metallic cell components, and becomes increasingly favored as H_2 is depleted and H_2O builds up in the fuel stream moving through an operating cell. The anode itself is a porous sintered nickel structure, which in today's cell is about 0.5 mm thick and 60 or 70 percent porous, with a mean pore size near 5 microns. The nickel is commonly stabilized against sintering and consequent shrinkage and loss of surface area by alloying with, for example, chromium and/or cobalt, or by using proprietary additives. The anode is supported by a nickel or stainless steel current collector, which carries the cell current to the bipolar stainless steel separator plate and hence to the next cell in the stack.

The cathode is a similar structure of NiO , currently about 0.3 mm thick and 70 to 80 percent porous. Cathodes are presently made by in situ oxidation of sintered nickel structures, but other methods are under investigation. The NiO of the cathode is in contact with Li_2CO_3 in the electrolyte, and

Half-Cell Reactions:

Figure A-1. Cell Schematic

thus contains some Li_2O in solid solution. It therefore has reasonable conductivity, perhaps of the order to $10 \Omega^{-1} \text{ cm}^{-1}$, but is nonetheless kept thin to minimize resistance.

The cathode gas, as can be seen from Fig. A-1, is a mixture containing CO_2 and oxygen. The CO_2 must come from the spent anode stream, and there are two general ways of transferring the CO_2 . The simplest is to burn the spent anode stream with excess air in a catalytic burner. The oxidant so obtained tends to be rather dilute, especially if the anode stream contained nitrogen. It may also be possible to separate CO_2 and water from the anode stream by use of a so-called product exchange device (PED). The separation is easy in principle, several processes are available, and the benefit in terms of cell voltage is considerable. The decision to develop and use a PED is like the decision to use oxygen-enriched cathode gas, in that it is a question of system cost versus system efficiency for the entire powerplant. Both questions are under study from a system analysis viewpoint, and cell data are being generated to define the performance of state-of-the-art cells operating with the appropriate gas compositions. It appears that a system using air and a burner can provide attractive performance.

The bipolar metallic cell separator must make low resistance contacts with the current collectors in both the high-humidity anode compartment and the highly oxidizing cathode compartment. Moreover, the thermal expansion of the separator must be compatible with that of the rest of the cell. The separator seals the fuel and oxidant in their compartments by pressing into the electrolyte tile face. This "wet seal" area is subject to strong corrosion couples, since considerable gradients in potential exists within the seal. It is necessary to protect at least the anode wet seal by, for example, aluminizing or aluminiding the seal area to form passive films on the metal

separator. Clearly, massive metal separators like those shown in Fig. A-1 are not economically feasible. Even a 0.5-mm-thick separator of Type 316 stainless steel sheet metal is still likely to be the most expensive component within the cell.

The electrolyte tile is perhaps the most interesting structure within the cell. It consists of about 40 wt percent of an inert particulate matrix material, currently LiAlO_2 , and 60 wt percent of a mixture of alkali carbonates, which are liquid at the cell operating temperature. The carbonate mixtures most commonly used are 62 mol percent or 50 mol percent Li_2CO_3 , with the balance being K_2CO_3 , although low-melting ternary mixtures with Na_2CO_3 have been used in the past, and are once again under study. The tile is surprisingly rigid at operating temperature, but is capable of yielding somewhat, in an inelastic manner, to conform to other cell parts under the stack holding forces.

Tile strength and electrolyte retention capabilities are closely related to the shape and size of the LiAlO_2 particles. The preferred shape appears to be long rods or fibers of submicron diameter which combine maximum tile strength and small pore size (to hold the liquid electrolyte by surface forces) with minimum tile resistance. The ability of the LiAlO_2 to maintain particle shape and size during operation is critical to cell life. Since there are at least three allotropic forms of LiAlO_2 , one of which, the alpha form, is of higher density than the others, tile preparation conditions must be controlled to give an allotropic form that is stable under operating conditions.

Tile thickness is directly related to resistance; therefore, it is desirable to use the thinnest tiles possible. However, the tiles must be strong enough to handle and must not allow cross mixing of anode and cathode gases

under cell operating conditions. The thickness currently being used is from 1 to 2.5 mm for tiles up to 0.1 m² in area. It is possible to reinforce the tiles with fibers of high-aluminum-content metal alloy. These fibers form a passive oxide coating, so that they do not short the anode and cathode; they also serve to strengthen the tiles, which otherwise might crack when the cell is thermally cycled. Tile thickness and the size distribution of the electrolyte-filled pores within the tile should match the thickness and pore-size distribution of the electrodes, so that some electrolyte is wicked into each electrode to establish a large surface area for reaction. Clearly, sufficient electrolyte must remain in the tile to prevent loss of strength or cross-diffusion of the gaseous reactants during the life of the cell.

APPENDIX B

Environmental Issues and Control Technology

To be supplied.

APPENDIX C

Market Application and Commercialization Strategy

1. Market Description

Baseload Power Generation

Two types of baseload molten carbonate fuel cell power plants are needed. Large baseload plants will be coal-fueled units of approximately 50 percent efficiency. This efficiency requirement implies steam-turbine bottoming. Steam turbines are scale-sensitive in cost and performance, and the bottoming cycle will provide only about 1/3 of the plant output, so the overall plant size must be greater than 500 MW. Construction of a plant of this size requires a longer time and represents a larger risk relative to smaller plants. It will therefore be preceded by operation of smaller powerplants. Operation of the first large plant represents a watershed in technology development beyond which a viable industry should be in existence which can proceed without federal support.

Small coal-fueled baseload plants (approximately 150 MW) can be built. These would have somewhat lower efficiencies (near 34 percent) because of the substitution of gas turbines for steam turbine bottoming, but would be modular and largely factory assembled. Construction leadtime of these plants would therefore be much shorter than that of the large plants. Short leadtime is a continuing advantage for all utilities. Also, a substantial number of applications for small baseload/intermediate plants is seen, because many utilities need small powerplants.

Dispersed Intermediate Generators

The significant advantages of molten carbonate power plants for this application are high-efficiency (45 percent) and low pollutant output. The

important requirements are cycling capability, low initial cost, (\$300/kW) and capability of dispersed siting. Each of these requirements implies liquid fuels, either coal-derived or petroleum, for any kind of intermediate duty powerplant. EPRI has a strong interest in this type of plant, and is closely coordinating their efforts with the DOE program. These plants are also factory assembled and modular, with short installation times. Powerplant size is inherently flexible because of modular construction, but the market is seen to be in the 5 to 50 MW range.

Industrial Cogeneration

This application is in the process of being defined more completely. Its salient characteristics are apparently the diversity of requirements in size, heat/electricity ratios, and duty cycle; the need for flexibility of output (heat or electricity); and uncertainty in non-technological factors, such as the nature of plant/electric utility interfaces. Nonetheless, tremendous energy savings are possible via cogeneration; national energy policy is increasingly supportive of cogeneration. Molten carbonate fuel cells seem very well-suited to the application because the temperature of available heat is high (greater than 600°C) and the electrical and heat outputs are variable over a wide range.

Application requirements will be developed beginning in FY 1979 by the contractors, the NASA/DOE CTAS study, and molten carbonate fuel cell program management.

A major advantage derived from both industrial cogeneration and dispersed generation activities is that the small size of these plants relative to baseload plants allows the credibility of a manufacturing capability for molten carbonate fuel cell technology to develop gradually before the construction of large baseload plants is undertaken.

2. Systems Description

Baseload Plants

A schematic of a large baseload plant is given in Figure A-1. The numbers are taken from the conceptual design used in the Energy Conversion Alternatives Study.* This design was an early effort, and is being replaced by the systems study and design work in progress in this program. Nonetheless, it serves to illustrate basic features of a baseload plant.

The plant size is determined by the steam turbine bottoming cycle, and by the coal handling and other auxiliaries, which are scale sensitive in cost and/or efficiency. The goals for large baseload plants are:

Efficiency:	50 percent coal to A.C. power
Initial Cost:	Competitive (\$800/kW installed)
Operating and Maintenance:	3 to 4 mills/kWh
Emmissions:	SO ₂ 0.1 lb/MBtu coal
	NO _x 0.03 MBtu coal
	particulate 0.01 MBtu coal
	heat 0.5 MBtu/MBtu coal (to air)

Based on these system goals, and on experience to date with molten carbonate fuel cells, the following cell performance goals are established:

voltage:	850 mV/cell
current density:	150 A/ft ²
fuel utilization:	85 percent single pass, low Btu gas
stack overhaul interval:	40,000 hr
stack cost:	\$60/kW (stack only)

*Energy Conversion Alternatives Study, United Technologies Phase II Final Report. NASA CR134955, FCR-0237.

As system design progresses, the cell goals will be updated and refined, for example, in some configurations the fuel utilization per pass may be lower. Cell performance seems likely to outstrip goal levels; this will certainly be reflected in design specifications and goals.

Small baseload plants with gas turbine bottoming cycles will have lower efficiencies (near 45 percent), but will require less on-site assembly and construction lead time. Emissions should be similar to those of the large plants, but cost may be somewhat higher due to economics of scale in fuel processing equipment.

Dispersed Generators and Cogeneration Plants

Dispersed generator development is an EPRI initiative at present. These powerplants will use liquid fuels, and will probably not have bottoming cycles, because of the requirement for rapid cycling (up to 70 percent of rating in a few minutes). Use of stack heat for fuels processing should allow high efficiencies to be achieved. DOE has not established a conceptual design or specific goals for this type of plant; although stack technology requirements are expected to be similar to those for baseload plants.

The cogeneration application will be defined in FY 1979. On an a priori basis it appears that the inherent flexibility of output and temperature of cooling streams are appropriate for the application. It further appears that the existence of small coal gasifiers is reasonably well assured. Preliminary plans call for demonstration in 1987, but are contingent upon requirement definition. No conceptual design exists as yet.

APPENDIX D

Program and Project Management System for DOE Outlay Programs

Figure D-1 is taken from a memo by Mr. Dale D. Meyers dated May 31, 1978. The subject of the memo was "Program and Project Management System for DOE Outlay Programs." This figure shows the phases through which a project may go, and based on the data on Figure D-1, the Molten Carbonate Fuel Cell Program is judged to be in Phase 3, Exploratory Development.

The following is also taken from the May 31, 1978 memo and describes the specific present and future phases for the program.

Phase 3: Exploratory Development

Efforts guided by the principle that the work should lead ultimately to a particular application or product. Even so, the techniques and intrinsic intellectual value of the work may compare favorably with that of basic research activity. Exploratory development can cut across several scientific disciplines and is intended to explore possible innovation in a particular area of one or more energy technologies.

Phase 4: Technology Development

Systematic use of the knowledge and understanding gained from research to achieve technical feasibility and to gauge economic and environmental potential of energy concepts, processes, materials, devices, methods, and subsystems.

Comprises development of engineering technologies, subsystems, planning and analysis studies, energy system concept formulation, comparison of alternative concepts, and development and test of laboratory-scale engineering feasibility models. This includes demonstration by experiment of alternative

MAJOR SYSTEM ACQUISITIONS — PHASE TRANSITION DECISION POINTS

Figure D-1. Program and Project Management System for DOE Outlay Programs

system concepts as well as preliminary studies encompassing system analysis, tradeoffs, preliminary cost benefit studies, planning, programming environmental studies.

Phase 5: Engineering Development

Systematic use of the knowledge and understanding gained from research and technology development to achieve the detailed design, construction, and test for performance, producibility, and reliability of energy system prototypes and pilot plants.

Detailed design, development and test of energy system prototypes and pilot plants judged to be technically and economically desirable as means of achieving the principal energy goals. Engineering development may concern itself with processes, preproduction components, equipment, subsystems or systems. The category also includes major system test facilities directed toward specific project development and the preparation of appropriate environmental impact statements.

Phase 6: Demonstration

Verification of economic and environmental visibility for commercial application, through design, construction, test, and evaluation, of large-scale energy systems in operational circumstances.

Final engineering design, assembly, test and evaluation of full-scale energy systems aimed at providing directly applicable experience in an operational environment so as to demonstrate economic viability for commercial application. Demonstration projects are intended to: a) overcome "scale-up" problems; b) contribute to the understanding of the economics of fabrication and operation; and c) resolve other questions such as public assistance, institutional and environmental issues. Preparation of suitable environmental impact statements is included in this category.

Phase 7: Commercialization, Production, and Operation

- a. Commercialization - When the predominant problems become those of bringing the system or project to commercial reality rather than demonstrating technical feasibility such as:
 - (1) "scale-up" problems are overcome;
 - (2) economics of fabrication and operation are understood;
 - (3) public acceptance, institutional and environmental issues resolved;
 - (4) commercial interest in project.
- b. Production - When the predominant problems become those of producing the items in quantity, bulk, or other parameters which meet specifically stated requirements.
- c. Operations - When the predominant problems become those of bringing the system or project from prototype or pilot plant operational testing status, to full-scale operational condition to meet stated objectives.