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Simulated Coal Gas MCFC Power Plant System Verification

**Final Report
July 30, 1998**

Work Performed Under Contract No.: DE-AC21-90MC27394

For
U.S. Department of Energy
Office of Fossil Energy
Federal Energy Technology Center
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0.1 Executive Summary

This Final Report discusses the 57 month, M-C Power Corporation work performed under DOE Contract No. DE-AC21-90MC27394, entitled *Simulated Coal Gas MCFC Power Plant System Verification*. The objective of the work effort was to further the commercialization of molten carbonate fuel cell (MCFC) technology through the design, construction, and operation of a 250-kW, natural gas-fueled, MCFC power plant.

M-C Power was the prime contractor with Bechtel Corporation of San Francisco, California, as engineering contractor. The 250-kW Balance of Plant (BOP) skid was designed and fabricated by Stewart & Stevenson Services Inc, of Houston, Texas. The Institute of Gas Technology provided R&D support for the fuel cell stack components. Unocal provided the Brea, CA site and support effort in the final construction and operation of the facility.

The research and development project is a major component of a general program for the development of commercial MCFC systems. In addition to DOE support, program sponsorship has come from the Gas Research Institute (GRI), the Electric Power Research Institute (EPRI), San Diego Gas & Electric Co., Southern California Gas Co., Southern California Electric Co., South Coast Air Quality Management District, and the State of Illinois.

The M-C Power MCFC stack design is called the IMHEX[®] concept (based on Internally-Manifolded Heat EXchangers). It is unique in this country and permits several power plant advantages over alternative fuel cell stack designs. The M-C Power Commercialization Plan includes scale-up of the IMHEX[®] technology to full-area cells and the assembly of these cells into power plant stacks.

This Final Report includes development, manufacturing improvement, and stack assembly techniques which have culminated in the design, procurement, construction and operation of a 250-kW MCFC Power Plant. Project activities include:

- ▶ Fuel cell market analyses and the formation of a users' group for marketing guidance.
- ▶ Manufacturing facilities expansion and upgrading for the production of the electrochemically active components of the MCFC stacks.
- ▶ Testing facilities construction and maintenance, including upgrading of the existing test station to accommodate 20-kW stacks; design and construction of an Acceptance Test Facility (ATF); and the physical construction of the 250-kW power plant at the Unocal facility in Brea, California.
- ▶ Technology development aspects of the program include:
 - Active component scale-up and verification employing bench-scale testing.
 - Separator plate hydraulic and mechanical design.

- Manufacturing issues, involving the design and fabrication of non-repeat stack elements.
 - Assembly issues, related to required tolerances in tall stacks.
 - Operations testing of four full-area stacks comprised of twenty cells to resolve issues of gas leakage within the cell, the longevity of fuel cell components, long-term voltage decay in stacks, electrolyte migration, and cathodic dissolution.
 - Laboratory and bench-scale testing directed at resolution of cost, performance, and endurance issues.
- An advanced research and technology development program was directed at fundamental MCFC technology which would improve performance and endurance at reduced cost.

Significant advances were made in MCFC technology engineering development during the course of the program which resulted in the following:

- Construction and operation four full-area 20-kW stacks, each of which provided data for scale-up to commercial-scale stacks.
- Duplicated the bench-scale test results in the electrode operating performance characteristics of the full-area stacks.
- Improved tape-casting and sintering of full-area electrodes that had operating characteristics which significantly exceeded the available bench-scale electrodes.
- Cell fit-up and melt-in techniques that resulted in improved stack structural integrity and minimized gas cross-over.
- Improved separator plate design and manufacturing tolerances for better hydraulic characteristics, better cell-to-cell gas distribution, and improved assembly procedures.
- Significant reduction, by a factor of four, of separator plate manufacturing costs.
- Design, construction, and operation of a facility for the preconditioning and preliminary testing of commercial size stacks. The 250-cell stack factory test had an average cell performance within 40 mV of expectations.
- Using systems analyses, defined four system configurations which approached 65% adiabatic system efficiency, based on HHV of natural gas fuel.

The 250-cell Unocal stack when operated at the acceptance test facility (ATF) produced 80 kW, or about 30% of rated capacity. This was primarily due to the limitations of the ATF. When installed in the Unocal facility it generated only about 4% of rated power. The reasons for this poor

operation were assessed and a failure analysis was conducted. The primary cause of failure was determined to be the uniform oxidation of all the anodes in the stack. It is believed that the stack could have recovered, at least partially, if the facility could have been kept in operation. The balance of plant equipment would not perform in accordance with design specifications. There was severe heat loss through piping insulation. The hot gas blower seal failed on numerous occasions and could not operate at design specifications. Significant problems with the instrument and control system could not be rectified.

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0.2.0 INTRODUCTION

0.2.1 Objective

The U. S. Department of Energy provided the following rationale in its solicitation for proposals under the Product Research and Development Announcement (PRDA):

The United States Department of Energy (DOE) has sponsored, and continues to sponsor programs for research and development which will lead to the commercialization of molten carbonate fuel cells (MCFC). DOE has recognized that the MCFC systems are a promising, potentially high-efficiency power generation system. Significant accomplishments have been made in the conceptual designs of MCFC systems. It is the objective of the work to be performed under the PRDA to lead to the commercialization of the coal gas MCFC system.

The objective of this procurement is to identify the current developmental status of MCFC systems and address those technical issues that need to be resolved to move the technology from its current status to the demonstration stage in the shortest possible time. The specific objectives are separated into five major tasks as follows:

1. Stack Research

It is the objective of the stack research work to identify and resolve issues in several areas. The stack research areas may include, but are not limited to 1) gas leakage within the cell, 2) the effects of coal-derived contaminants on operation, 3) the longevity of fuel cell components, 4) long-term voltage decay in stacks, 5) electrolyte migration, and 6) cathodic dissolution. Stack research is expected to involve laboratory-scale and subscale MCFC tests.

2. Power Plant Development

It is the objective of the power plant development work to demonstrate and verify improvements in the MCFC technologies, through activities that include the following: component/stack design; full area component fabrication and stack assembly; and full-scale and full-height (100 - 300 kW stacks) testing in a (natural gas), simulated MCFC power plant system.

3. Test Facilities Development

It is the objective of the test facilities development work to address any issues impeding the development of testing facilities to support MCFC stack research and power plant development. It is the objective of the PRDA to support responsive and reasonable facilities development where fiscally possible.

4. Manufacturing Facilities Development

It is the objective of the manufacturing facilities development work to address any issues impeding the development of manufacturing facilities to support MCFC stack research and power plant development. It is the objective of the PRDA to support responsive and reasonable facilities development where fiscally possible.

5. Commercialization

It is the objective of the PRDA to aid in the development of commercialization strategies having a high probability of success with well-defined goals based on market analysis, identification of power plant development requirements for markets, and analysis of competing systems.

0.2.2 Background

This Final Report discusses the M-C Power Corporation effort under DOE Contract No. DE-AC21-90MC27394, entitled *Simulated Coal Gas MCFC Power Plant System Verification*.

The effort is part of a general program for the development of commercial MCFC systems, with additional cooperative sponsorship from GRI and EPRI. Additional participants include:

- San Diego Gas & Electric Co.
- Southern California Gas Co.
- Southern California Electric Co.
- South Coast Air Quality Management District
- State of Illinois

This final report covers the entire subject of the Unocal 250-cell stack. Certain project activities have been funded by organizations other than DOE and are included in this report to provide a comprehensive overview of the work accomplished.

This report is organized as follows:

Each task is a chapter in the report, with the chapter number corresponding to the task number. Similarly, the chapter first-level subnumbers correspond to the subtask numbers. Illustrations follow the text in each chapter. Chapters are paginated individually, in the format "Page 3-12"; similarly, figures and tables are numbered by chapter.

An exception is Task 5, because most of the subtasks are quite large. In this case, the illustrations follow the text at the subtask level. Pagination and figures are at the subtask level, *i.e.*, Figure 5.1 - 6 or Page 5.5 - 8.

This Chapter 0 contains the *Executive Summary, Introduction, Objective, and Background.*

This report covers the entire work effort sponsored by DOE and others. Many of the subtasks have been separately reported to DOE. For example, Subtask 5.5 covered the operation of four full-area, subscale 20-kW stacks. Stack Test MCP-3 was primarily funded by GRI and was separately reported to them. That report, and similar documents to DOE for Tests MCP-4, MCP-5, and MCP-6, form the basis for the current document and much of the discussion in those reports is not repeated here. Similarly, the plant design document and operating plans were reported to DOE. Only the executive summaries of these documents are included herein.

0.2.2.1 The Technology

The internally manifolded MCFC stack concept is a simple approach to the series connection of cells, and to the supply of reactants and removal of products to and from a stack, which avoids the installation of external manifolds on all four sides of the stack. Instead, it relies on manifolds created by the cells themselves as the stack is assembled. It also uses a configuration presently producible in large sizes for plate and frame heat exchanger products. In addition, the internal manifolding characteristics of the IMHEX[®] concept offers the potential for reduced use of metallic repeating components, to reduce cost. It allows the use of carbonate tapes to supply electrolyte to the stack where it should be placed. This approach significantly reduces carbonate creepage and eliminates corrosion which are two high priority issues with MCFC technology.

Externally manifolded stack concepts face two major problems;

- 1) Their gas manifolds require three dimensional clamping forces and are unable to accommodate the stack height changes that take place during start-up and operation.
- 2) The carbonate pumping and transfer that take place through the manifold gaskets and result in corrosion and lower stack performance and life.

The IMHEX[®] internal manifolding approach solves these two problems because there are no external clamp-on manifolds and no external gaskets. The success of the IMHEX[®] stack concept in eliminating carbonate pumping was dramatically shown in the performance of M-C Power Stack Test MCP-2, a 70-cell, subscale ($\approx 1 \text{ ft}^2$) stack that operated, under EPRI funding, for 1,275 hours without carbonate pumping; and in stack test IGT-6 20-cell subscale stack that operated under DOE and San Diego Gas & Electric funding for 7,000 hours with no carbonate pumping.

The gas sealing in an IMHEX[®] stack is provided by the electrolyte matrix of each cell. Access of anode or cathode gases to the opposite side of the cell is prevented by suitable blanking of the separator plate in the gas manifold areas. Because the electrolyte matrix is always 100% filled and because it is always under the same compressive load in the seal areas as in the active areas, IMHEX[®] stacks provide excellent gas sealing. Thus, IMHEX[®] stacks will operate at high overall efficiencies because of higher gas conversions and lower gas leakage.

In summary, internally manifolded stacks like IMHEX® provide a technically viable and economically feasible route to MCFC commercialization because they avoid the problems *inherent* in externally manifolded concepts. IMHEX® is preferred because

1. Elimination of electrolyte pumping has been demonstrated.
2. IMHEX® stacks utilize electrolyte matrix tapes to control the deployment location exactly where desired, and no carbonate losses are observed. Superior endurance is therefore possible while corrosion is eliminated as a technical issue.
3. The close component tolerances required by external manifolding in the manifold areas are eliminated.
4. Only unidirectional (z-direction) holding forces are required. Externally manifolded systems require holding forces on all four manifolds (x and y-directions) as well as in the z-direction.
5. The electrolyte matrix alone provides the gas seals required for high operating efficiencies. Experimental data shows that gas seals in 1 ft² IMHEX® stacks tolerate 500% higher pressure gradients than seals in prototype externally manifolded stacks.
6. IMHEX® stacks have the intrinsic capability of following component shrinkage without loss of sealing or electrical contact.
7. IMHEX® separator plates are practical and will be economical because they have been modeled after a technology which is here today, plate-and-frame heat exchangers. They require no breakthrough in fabrication technology.

0.2.2.2 Program History

This project, DOE Contract No. DE-AC21-90MC27394, is the second in a series of awards under an overall DOE program for the development and commercialization of molten carbonate fuel cells. The start date of the project was September 14, 1990, and the nominal completion date was December 31, 1995. Contract completion was extended to April 30, 1998.

The initial project in this series was awarded to IGT, with M-C Power and Combustion Engineering, Inc. (C-E) as subcontractors. That effort, DOE Contract No. DE-AC21-88-25026, ran from April 1, 1988 to October 31, 1990.

The IGT effort under that contract was the design, development, and operation of the IMHEX® sub-scale components and the testing of stacks made from those components. IGT continued their development of advanced components at the bench-scale and was responsible for overall project management.

The primary C-E effort during this phase of the program was the analysis of coal-based MCFC systems for overall direction of the program. C-E also undertook a preliminary market analysis and a manufacturing cost estimate. They initiated effort toward plate manufacture, welding, cutting, and aluminization, both on the sub-scale and full-area plates.

M-C Power moved to its facilities in Burr Ridge, Illinois, and started to improve those facilities and expand its staff. Tape-casting equipment at the time the largest in the world for the manufacture of anodes, cathodes, matrices, and electrolyte tapes was installed. Simultaneously, a continuous-belt sintering furnace for the curing of electrode components was installed. M-C Power, together with Lummus-Crest Div. of C-E, designed, constructed, and installed the process skids for the full-area test facility and installed the testing room for those stacks. Also, M-C Power designed the first iteration of the full-area plate and issued the contract for the manufacture of the dies to produce those plates. In the test area, M-C Power operated a 20-cell, sub-scale stack at the IGT facilities and a 70-cell, sub-scale stack in a shake-down of its own facilities.

0.2.2.3 Program Modifications

Several events, both technical and programmatic, occurred during the course of the effort that impacted the project. Some of the major program modifications were:

- ▶ Program team reorganization.

The program team originally included C-E, a major supplier of power plants, both nuclear and fossil-fired. The C-E commitment to the program was strong, as evidenced by its 24.5% ownership of M-C Power. Its role in the program included product marketing, sales and distribution of power plants; separator plate manufacture, and power plant engineering and construction.

Early in the program (November, 1990), C-E was purchased by Asea Brown Bovari (ABB) of Switzerland and Sweden. ABB, at the time, had a significant solid oxide fuel cell program which was discontinued and notified M-C Power on May 15, 1991 that it would discontinue its MCFC work after it completed its scope of work under the DOE contract. This position was unacceptable to M-C Power, DOE and the rest of the program team. Consequently, on August 21, 1991, ABB-C-E was notified that its subcontract was terminated.

A significant effort was expended in reassembling the program team. The plant engineering effort was undertaken by the Bechtel Corporation, which also acquired the ABB-C-E ownership position in M-C Power. Stewart & Stevenson Services, Inc. (S&S), a major supplier of packaged gas turbine power plants was engaged to take over some of the work previously assigned to ABB-CE including BOP fabrication, marketing, sales and distribution. M-C Power took responsibility for separator plate manufacture, including parts forming, cutting, welding, corrosion protection, and annealing.

► Facility Pressurization.

As originally envisaged, the MCFC was to operate at atmospheric pressure. Early cold-flow modeling work, as confirmed by the operation of the first 20-kW test stack, indicated that the pressure drop across the cathode side of the stack would be excessive at the high cathode flow rates required for stack cooling at higher current density. Consequently, it was decided to operate the 250-cell stack and associated BOP equipment at 3 atmospheres pressure to reduce the pressure drop by a factor of three, to reduce the recycle blower size and parasitic power demand, and improve stack voltage, and increase system efficiency.

► Acceptance Test Facility (ATF)

The original program plan anticipated installing the stack in the field without factory conditioning. The environmental aspects of the conditioning steps precluded this option. It therefore became necessary to construct a conditioning system for the 250-cell stack at the M-C Power factory. This ATF provided the capability to heat the stack to operating temperature, effect binder removal, and operate the stack at low current.

► Fuel Re-emphasis

The original program was based on a dual-fuel application, operating on both natural gas and simulated coal gas. ABB-C-E had included in its proposal a significant engineering effort in support of the dual-fuel operation. This included subtasks for coal gas MCFC optimization, TAG III engineering, and a repowering concept. As the program progressed, the dual-fuel nature of the plant was de-emphasized and eliminated.

► Test Program Redirection

The initial effort called for a series of three sub-scale stacks operated at IGT. However, when it was found that full-area hardware was practical, the test program concentrated on full-area stack testing.

1. TASK 1. COMMERCIALIZATION

The objective of this task was the development of commercialization strategies with a high probability of success, the development of well-defined goals based on market analysis, the identification of power plant development requirements for markets, and the analysis of competing systems. The base program objectives were to focus on purchaser issues.

1.1 Subtask 1.1 Prioritize Purchaser Issues for MCFC Power Plants

Objective:

To identify those issues which are most important to the potential purchasers of MCFC power plants and to prioritize those issues in terms of the users' perspective.

Discussion:

Two market surveys were specifically designed to identify purchaser issues and the priority they have in influencing purchasers to buy MCFC power plants. The first survey, conducted in late 1991, was a 10-page questionnaire containing forty-three detailed questions. The questionnaire was designed first to identify potential customers for the IMHEX[®] fuel cell technology. It was also structured to provide guidance with respect to system design options. The intent was to solicit input from potential purchasers as to the characteristics they desired in MCFC power plants.

Questionnaires were distributed to firms interested in power generation and energy conversion equipment. An attempt was made to reach individuals who were familiar with fuel cells in general, and M-C Power's technology developments if possible. Thirty-seven firms responded to the questionnaire yielding a response rate of approximately 50%.

The respondents are categorized as follows:

- ▶ 48% Electric Utilities
- ▶ 24% Gas Utilities
- ▶ 19% Combined Utilities
- ▶ 3% Independent Power Producers (IPP)
- ▶ 3% Industrial End Users
- ▶ 3% Other.

This survey and its responses were used to develop a profile of potential MCFC purchasers.

The initial potential market identified involved distributed generation. This is defined as the segment of the electric power market where strategically placed small generating units offer a cost-effective alternative to the traditional utility practice of meeting incremental load growth. A target market was identified to include applications that place the highest value on prime power where the

fuel cell unit can serve as the baseload electrical supply for the application. These applications include large commercial buildings with less than 2 MW peak demand, such as hotels, hospitals, office buildings, and retail malls.

Fuel cells are better suited to commercial applications than conventional technologies since their thermal to electric ratios are a closer match to the applications' load profiles. When specified for cogeneration applications, gas turbines and reciprocating engines are most economical when the thermal load of the application is closely matched to the unit's thermal output. Fuel cells are not limited by this operating characteristic because they possess an inherently higher electrical efficiency. Another factor that makes commercial applications attractive is the fact that their purchased cost of electricity from the local utility is higher than that of industrial customers. This places a higher value on the electricity generated by a fuel cell power generator.

Other applications deemed suitable for MCFCs include medium to small industrial manufacturing facilities. Fuel cells are best suited to these applications where traditional electrical rates exceed the national average or when a value can be placed on premium reliable power. The fuel cell is sized to displace the base electrical load of these facilities. They can also be dedicated to serve specific loads within the facility that can not tolerate the electrical disturbances that are normally associated with the grid connected electric supply.

Another attractive application is in electric substations where traditional transmission and distribution investments in upgrades can be deferred. Some of the benefits or savings that can be derived include a decrease in transmission system losses, VAR control, distribution feeder savings, and area regulatory savings which are determined on a specific utility system basis. Other substation savings can be derived from eliminating the need to replace transformers, pursue substation upgrades, or build entirely new substations.

Compressor stations at gas pipeline companies were identified as potentially attractive applications. In this use the fuel cell would take advantage of a low cost wholesale gas supply and in return would service the electrical and thermal load of the station.

The survey results revealed that the most significant marketplace issues, or "drivers," used to assess fuel cells are reliability, environmental and regulatory concerns, energy conservation and demand side management, and customer service. Although environmental concerns ranked highest in the survey, only a small percentage of the respondents said they would derive any value from paying attention to them. The only applications that derived any value were in areas that are classified as non-attainment basins. Even then, the respondents had difficulty assessing any economic value to the environmental benefits derived from MCFCs.

Based upon survey responses, M-C Power began formulating a preliminary market development strategy based upon a market-responsive product definition. The development of target goals for a market entry became a major part of the strategy. Product design goals are summarized in the Table 1.1-1.

Table 1.1-1 Product Design Goals

Economic Attributes	Target Goals
Capital Cost	\$1,500-\$2,000/kW
Return on Investment (ROI)	Utilities 13%-18%, IPP 16%-25%, End User 25%-30%
O&M Costs	~1¢/kWh
Operating Characteristics	
Complexity	Simple Design; Unattended Operation
Performance	45%-55% electrical efficiency, (HHV); 75%-85% overall
Maintenance Requirements	Minimal; 3 to 4 scheduled visits per year.
Real Estate Requirements	Minimize; ~1 kW/ft ²
Personnel Requirements	Utility service personnel;

A second survey was conducted in early 1993 to assess alternative design options for the market entry product. This was to be accomplished by soliciting input from organizations which had expressed interest in M-C Power's fuel cell technology through participation in the Alliance to Commercialize Carbonate Technology (ACCT) organization. The survey was designed to offer descriptive specification sheets, each containing several different options. The respondents were asked to review and analyze each specification sheet and provide feedback as to what operating characteristics or specification options were most critical in their evaluation process.

Based upon the most significant issues raised from the market survey conducted in 1991, five options were presented to ACCT members. These options consisted of three different baseline design options, A,B, and C, with the remaining two being variations of options A and C. The difference or trade-offs represented in the three base design options included:

- ▶ Efficiency of the unit versus part load
- ▶ Capital cost of the unit
- ▶ Capacity of the unit
- ▶ Environmental emissions
- ▶ Packaging approach

Baseline product goals prior to the survey included:

▶ Unit capacity	between 500 kW to 2,000 kW
▶ Electrical efficiency	between 45 to 55%, HHV
▶ Initial selling price (FOB), 1991 dollar	\$2,000/kW
▶ Initial loaded fabrication cost, 1991 dollar	< \$3,000/kW
▶ N th unit selling price (FOB), 1991 dollar	< \$1,300/kW
▶ Layout or foot print	< 1 kW/ft ²
▶ Gross availability	> 90%

- ▶ Mean time between failures > 2,000 hrs
- ▶ Initial stack endurance > 20,000 hrs
- ▶ Grid-connected with emergency independent operation

Option A is a baseline power plant that was used to develop a 1 MW power plant design and model. This was considered to be the performance option. The capital cost was estimated to be \$1,700/kW (1991 dollar) and was derived by averaging the cost of units 50 through 500. The packaging reflects the comments of some of the ACCT members. It is also an integrated design which minimizes piping. The stack/reformer vessel (power module) has four 200 cell stacks side-by-side and a 160 plate reformer in the fifth stack position. The overall dimensions for the system are 20 feet wide by 40 feet long by 12 to 14 feet in height. The maximum electrical efficiency is 50% HHV. Thermal output is 150 psia steam at 1.37 MMBtu/h. Emissions are 1 ppm NO_x at 15% O₂, equivalent to 0.021 lb NO_x per MW-hour. Ramp rate of 5% per min or 50 kW, and equivalent availability of 90%.

Option B is considered the "low cost" option of the 1 MW design. This option is based on a unit that greatly increases the power available from the turbo-machinery. An assumption is made that about half the power comes from the fuel cell and half from a gas turbine-type device. The fuel cell consists of two stacks with 250 to 300 cells each. The cost is based on option A integrated with a 25% efficient turbine at \$400/kW (1991 dollar). The big advantage of this option is the impact on capital cost, which is lowered to \$1,150/kW (1991 dollar). The disadvantage is that the maximum electrical efficiency of 55% HHV begins to decline at loads above 60% of rated capacity, dropping below 40% efficiency at full load. Thermal output is 350 psia steam at 0.93 MMBtu/h. Environmental emissions increase three-fold to 3 ppm NO_x at 15% O₂, equivalent to 0.063 lb NO_x per MW-hour. Ramp rate and equivalent availability remain the same at 5%/50 kW per min and 90% respectively. The overall foot print area decreases with an increase in length offset by a larger decrease in width.

Option C is similar to option A with the exception of an assumption that the fuel cell is able to achieve higher current densities, the effect of which is a reduction in the number of cells needed: 650 versus the 800 used in option A. Therefore, the differences between options A and C are the following; the capital cost of option C is \$1,550/kW (1991 dollar); it has 50% electrical efficiency HHV; and layout alterations yield a slight decrease in foot print area.

Two additional options were incorporated into the survey; they were classified as A2 and C2. The reasoning for these classifications were that the options shared the same specifications as options A and C, with the exception of one variable. A2's rated capacity was double that of option A, resulting in a decrease in cost per kilowatt. C2's rated capacity was half of option C, resulting in an increase in cost per kilowatt.

The survey indicated that 63% of the respondents selected the performance option A2, over the lowest cost option B (chosen by 15%), and over the lower capacity option A (chosen by 7%). Of the 63% of the respondents that chose A2 first; 53% selected performance option A second; 29% selected cost option B second, and 11% selected cost over performance option C second.

From the results of the second survey M-C Power arrived at the following conclusions:

- ▶ Maintain steady performance over a wide load range.
- ▶ Look into increasing capacity >1 MW , if it reduces cost per kilowatt.
- ▶ Capital costs are too high.
- ▶ Both lower profile and smaller footprint are desired.
- ▶ Availability of 90% is acceptable, but 95% is desired.
- ▶ A ramp rate of 5% is too low and needs to be 20%.
- ▶ By-product heat was an important characteristic in over half of the assumed applications.

In summary, the two surveys have yielded significant results which were used to prioritize purchaser issues for MCFC power plants. The issues of reliability and durability were identified as the strongest drivers for a relatively new technology such as the IMHEX[®] fuel cell. They are the most likely to trigger a "go-or-no-go" response to purchasing the technology. Environmental and efficiency issues are also very strong market drivers. They are essentially the issues that trigger an investigation of using technology or assessing its benefits. Cost is becoming an increasing driver and will trigger a no-go response if it is perceived to be out of line in comparison to conventional technologies, having proven reliability and reasonably efficient. However, the increase in efficiency of the conventional technologies may be negated by an increase in cost required to yield a more efficient unit. The surveys also indicate that a rated capacity of 1 to 2 MW is a reasonable size. This holds true especially if the larger size leads to a lower cost per kilowatt.

M-C Power has incorporated the results of these two surveys into its current product development and commercialization planning efforts. Specifically, it has helped guide the initial power plant design efforts and focused attention on a need to educate and assist potential end-users of molten carbonate fuel cells on how to assess the benefits of the technology for various applications.

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2 TASK 2. POWER PLANT DEVELOPMENT

The objective of this task was to demonstrate and verify improvements in MCFC technology through component and stack design; full-area component fabrication and stack assembly; and full-area and full-height (100-300 kW) stack testing in a partially integrated MCFC power plant system.

2.1 Subtask 2.1 Optimize Current EPRI TAG II Level Coal Gas MCFC (CGMCFC) Systems

Objective:

To further analyze CGMCFC steam bottoming and combined cycle systems, select the best commercially viable system, subject the chosen system to more stringent analysis, and establish conditions for testing of the 250-kW power plant.

Discussion:

Prior to the start of the program, M-C Power, at the request of the Morgantown Energy Technology Center (METC), undertook an in-house effort in re-assessing competing technologies so that all of the engineering reports were assessed on a comparable basis. Figure 2.1-1 presents the result of that analysis. Also, in this effort, a natural gas-based MCFC system was assessed and compared to alternative emerging gas turbine systems. The MCFC system appeared preferable to even Advanced I-STIG at plant sizes smaller than about 150 MW.

Early in the program, ABB-CE undertook several studies to analyze the systems initially selected in the previous program:

- ▶ The PSI model (only the main-frame version was then available) was reassessed for improved convergence.
- ▶ Modified constants were input to the model to more accurately represent current state-of-the-art MCFC hardware and electrochemical performance.
- ▶ Sensitivity studies varied the following conditions:
 - Air/fuel ratio
 - Gasifier steam/carbon ratio
 - Steam injection point for soot deposition suppression in the gasifier/clean-up section of the CGMCFC facility
 - MCFC operating pressure

Figure 2.1-1 Comparison of Coal-fired MCFC Systems with Alternative Technologies

Neither of the two CGMCFC systems exhibited a distinct advantage. Operating conditions for simulating a feed to a CGMCFC were determined for input into the 250-kW design. Further effort was placed on hold, pending additional information on the market analysis. By that time ABB-CE had left the project and had been replaced by Bechtel, and the dual-fuel requirement of the plant was eliminated. Therefore, no further effort on this subtask was expended.

2.2 Subtask 2.2 Select/Inspect Power Plant Test Site

Objective:

To inspect the 250-kW power plant test site and establish site-specific requirements and constraints to be incorporated in the power plant design so that it meets test objectives.

Discussion:

2.2.1 General Description

M-C Power sited a 250 kW nominal capacity molten carbonate fuel cell demonstration power plant at the Unocal Fred L. Hartley Research Center in Brea, California. The plant was designed to convert approximately 2000 m³/d (70,000 SCFD) of natural gas into hydrogen and carbon monoxide and produce 250 kW of power from the MCFC. The fuel cell was also expected to produce about 126,000 kcal/hr (500,000 Btu/hour) of by-product heat.

The plant consisted of an MCFC stack, reformer, blowers, heat exchangers, inverter, electrical components, and an instrument and control system. The demonstration plant was natural gas-fueled.

2.2.2 Location and Access

The Unocal Fred L. Hartley Research Center in Brea, California is located in the northeast part of Orange County and is 40 miles east of Los Angeles and 25 miles south of Ontario. It can be reached either from Los Angeles, Orange county, or Ontario Airports. It is about 25 miles north of John Wayne Airport in Orange County. The plant was located near the north end of the complex. Imperial Highway and Valencia Avenue provide access to the Unocal facility.

2.2.3 Specific Site Criteria

2.2.3.1 Climate

Temperature Range	0°C to 43°C (32°F to 110°F)
Precipitation: Annual Average	25 cm (10 in)
Site Elevation	120m (395 ft)(MSL)

2.2.3.2 Seismicity and Wind

The site is located in Uniform Building Code (UBC) Seismic Zone 4 area. Structural and seismic design was in accordance with the applicable sections of the UBC, unless otherwise noted in the covering purchasing requisition or specification. For seismic design, the Occupancy Importance Factor = 1.0 and CS = .14.

The mean wind speed is 8 km/hr (5 miles/hr). All plant facilities were designed for wind loads in accordance with the UBC, using a basic wind speed of 104 km/hr (65 mph), exposure C, and Importance Factor of 1.0.

2.2.3.3 Water Table and Soil Condition

The water table elevation is at approximately 60 m (200 feet).

Existing soil consists of alluvium, underlying a few centimeters of fill. Below foundations and slabs on grade, the soil was removed, conditioned, and recompacted.

2.2.3.4 Utilities Available at the Site

Unocal provided all utilities at the site boundary.

2.2.3.4.1 Fuel Supply and Analysis

Natural gas was available at the site at 413 kPag (60 psig) pressure. A typical analysis of this gas is given below.

Constituents	Percent (Volume)
Methane	94.796
Ethane	3.200
Propane	0.628
I-butane	0.060
N-butane	0.100
Carbon Dioxide	0.827
Nitrogen	<u>0.389</u>
Total	100.000
Higher Heating Value	9204 kcal/m ³ (1034.4 Btu/scf)
Lower Heating Value	8306 kcal/m ³ (933.4 Btu/scf)
Temperature (assumed)	16°C (60°F)
Specific Gravity	0.587 (relative to air)

Sulfur Compounds

Mixed Mercaptans	2.15 ppm
Tetrahydrothiophene and other sulfur compounds	2.60 ppm

2.2.3.4.2 Steam Supply

Steam was available from an existing cogeneration plant in the research center at 862 -1034 kPag (125 - 150 psig) pressure. Steam contains 0.07 ppm chloride and 0.06 ppm sulfate. The limits for the fuel cell are 0.1 ppm for both chloride and sulfate. Steam produced at 1034 kPag (150 psig) in the fuel cell project was supplied to the cogeneration plant.

2.2.3.4.3 Boiler Feedwater Supply

Boiler feedwater was available from the cogeneration plant at 87°C (188°F) at 1930 kPag (280 psig). This water had been treated only in a softener and had been deaerated. Before deaeration, the softened water contains 43 ppm chloride and 48 ppm sulfate. After deaeration, the water contains 18 ppm chloride and 43 ppm sulfate. The feedwater had 0.005 mg/l copper, 0.04 mg/l iron and 2.3 mg/l silicon. At least 5% blowdown was required to maintain steam quality.

2.2.3.4.4 Cooling Water Supply

Industrial water was available in small quantities, 37.9 to 45.5 lpm (10 to 12 gpm), at ambient temperature and at 689 kPag (100 psig) pressure at the site boundary for cooling purposes.

2.2.3.4.5 Distilled Water Supply

A supply of distilled water was available, if required by the fuel cell power plant.

2.2.3.4.6 Fire Protection Water

A 200 mm (8 in) fire protection water main was available within 23 m (75 feet) of the site. Water pressure in the main was 551 kPag (80 psig). Fire hydrants were available near the site.

2.2.3.4.7 Potable Water

No domestic, potable water was available from Unocal.

2.2.3.4.8 Storm Water Disposal System

Based on the site inspection and discussions with Unocal, it was decided to use the existing site storm water drain system without modification for the fuel cell project.

2.2.3.4.9 Other Plant Drain Disposal System

The blow-down system, capable of handling 4545 kg/hr (10,000 lb/hr) flow of an existing, standby boiler was situated adjacent to the site. This system could be used to drain other drains from the fuel cell project. No domestic sanitary sewer was provided by Unocal. Based on discussions with Unocal, it was decided that the fuel cell project did not require a sanitary sewer system.

2.2.3.4.10 Compressed Air and Gases

Dry plant air and instrument air were available from Unocal at 689 kPag (100 psig) pressure. Maximum air flow for the fuel cell project was limited to about 34 m³/min (1200 SCFM) during plant start-up and abnormal operating conditions. Normal plant air consumption was expected to be 1.7 m³/min (60 SCFM).

Nitrogen was available at a flow rate of 5.7 m³/min (200 SCFM) from Unocal through a 25mm (1 in) line at 827 kPag (120 psig) pressure and at ambient temperature.

Carbon dioxide was not available from Unocal and was supplied in cylinders, 6.8 m³ (240 ft³) per cylinder.

2.2.3.4.11 Electric Power Supply

Power supply available at the site:

- ▶ 480 volts, 3 phase, 60 Hz

Voltage preference for motors:

- ▶ Motors less than ¾ Hp; 115 V, single phase, 60 Hz
- ▶ Motors ¾ to 250 Hp; 460 V, 3 phase, 60 Hz

Electric power supply from the fuel cell project shall meet utility standards.

2.2.3.4.12 Area Classification

The basis for the area classification was recommended practices outlined in API RP-500A. Electrical equipment, devices and installation methods was conformed to Article 500 of the National Electrical Code.

Motor control centers and panel boards were located in unclassified areas. Control panels were also located in unclassified areas, whenever possible.

2.3 Subtask 2.3 Develop Dual-Fuel Power Plant Design

Objective

To develop a complete design and design document for the 250-kW power plant. The design was categorized into subsystems and included piping & instrumentation diagrams (P&IDs), flow sheets, and elementary wiring diagrams.

Discussion:

A conventional process design approach was followed by Bechtel in the development of the detailed design for the Unocal power plant. First, M-C Power's fuel cell design and operating requirements were reviewed. Then, a process description and a process flow diagram (PFD) (Figure 2.3-1) showing heat and material balances for seven operating modes were prepared for project use. Preliminary process control concepts were developed. The plant included a fuel cell stack, reformer, blowers, heat exchangers, electrical components, and inverter which were on four pre-fabricated modules.

A project design criteria document was developed to define the overall plant size, location, fuel composition, site atmospheric conditions, site utility and interface requirements, and applicable codes and standards for the design. A preliminary plant layout was prepared. Figure 2.3-2 is a partial isometric view of the MCFC and control skid.

Based on the approved flow diagram, process description, and design criteria documents, equipment specifications were prepared as part of the bid documents that were issued for bids. Bidders' offers were evaluated and purchase orders were placed. Equipment vendor drawings were reviewed to be certain that all equipment was built in accordance with the specifications and interface requirements were met.

Piping and instrument diagrams (P&IDs) were developed based on the PFD and equipment information provided by the vendors.

Close design coordination was maintained among the various participants of the project by monthly and quarterly project review meetings and by soliciting comments on the design documents prepared for the project.

Figure 2.3-1 Plant Process Flow Diagram

Figure 2.3-2 Partial Isometric View of Facility

The several operating states of the facility were defined and start-up procedures were written. A HAZOP analysis was undertaken and failure modes were assessed.

The major features of the power plant are

- ▶ A nominal 250-kW molten carbonate fuel cell power plant is fueled by natural gas.
- ▶ The system operates at a moderately elevated pressure of about 207 kPag (30 psig) to reduce the line sizes and parasitic power load for the recycle compressor.
- ▶ The system is not optimized for efficiency; rather, it is a proof of the concept of operating the MCFC on a natural gas reformer effluent. Operability was stressed over tight thermal integration.
- ▶ The facility is a net producer of heat, which is recovered as cogeneration steam.

2.4 Subtask 2.4 Develop Detailed Power Plant System Construction Plan

Objective:

To develop a detailed construction plan for the 250-kW power plant. The plan shall include plot plan, general arrangement drawings, civil construction plan, module definition, materials list, and construction schedule.

Discussion:

The detailed power plant construction plan for the demonstration project was prepared by Bechtel under Subtask 2.4 and included the following activities:

- Providing detailed engineering for the plant control system, electrical system, foundation, structure and piping.
- Developing a detailed site layout.
- Developing skid design and layout.
- Preparing bid packages for the mechanical, civil, and electrical subcontracts and assisting in bid evaluation and procurement.
- Preparing the construction plan.

The construction plan included the following:

- System P&IDs including drawings prepared by equipment suppliers.
- Electrical single line, schematics and block diagrams, and cable routing including drawings prepared by equipment suppliers.
- Detailed plant layout, pipe routing and isometric drawings including drawings prepared by equipment suppliers.
- Civil grading and equipment foundation drawings.
- Miscellaneous interconnecting piping support drawings.
- Control and logic diagrams including drawings prepared by equipment suppliers.

- Technical documents for the construction and installation bid package including preliminary bid evaluation.
- Mini technical packages for individual subcontractors.

Discussion of the Activities

Process design was finalized and equipment purchase orders were issued at the end of Task 2.3. Preliminary P&IDs were prepared under Task 2.3 and the drawings were refined and finalized under Subtask 2.4. Equipment suppliers' drawings were received and reviewed for the interface information and for the design and development of the electrical single line and block diagrams, final plant operation logic diagrams and foundation design for the equipment. When necessary, equipment supplier representatives were advised to visit Bechtel offices and discuss design, constructability and operability of their system.

The Distributed Control System (DCS) cabinets were built and tested for logic functions at the manufacturer's plant. A document was prepared for Unocal to include all technical specifications and drawings required for the preparation of their subcontract bid package. Joint review of the bid package and site was conducted with the prospective bidders at the prebid meetings. After bids were received they were evaluated for technical content, scope completeness and price. Unocal acted as the general contractor and hired separate subcontractors for civil, mechanical, piping, instrumentation, electrical, insulation, and painting work to avoid scheduling problems. Individual subcontract packages were prepared for Unocal's use.

2.5 Subtask 2.5 Design, Fabrication, and Assembly of Full-Scale, Full-Height 250-kW MCFC Stack Module

Objective:

To complete the design of the 250-kW MCFC stack module based on the present full-area cell and full-height stack design, to fabricate separator plates and active area components, and to assemble the full-scale 250-kW module for delivery to the test site.

Discussion:

2.5.1 Prepare Component Design Requirements (CDR) Document

Early in the course of the program, the Component Design Requirements (CDR) Document was replaced by a Design Control Document (DCD) to emphasize the control function of the document. The DCD included all components of the MCFC stack, from non-repeat elements to the overall vessel-enclosed stack.

The DCD is a compilation of drawings, engineering specifications, mixing formulations and fabrication procedures which represent the state-of-the-art technology for the manufacture of IMHEX® MCFCs. The DCD is intended to act as the primary reference tool for guiding and controlling the methods, procedures and materials for the manufacture of fuel cell stacks and the Unocal 250-kW demonstration facility.

The contents of the DCD were continuously updated and maintained, reflecting the latest, actual work in progress. As such, preliminary design requirements developed by M-C Power became displaced by more detailed equipment specifications generated by Bechtel, Stewart & Stevenson, Unocal or Xytel for components and plant design within their scope of supply. Xytel was responsible for the design and fabrication of the ATF installed at M-C Power.

The first-issue of the DCD was completed in February, 1993. It was an eight-volume document, covering all aspects of the MCFC engineering, design and construction. When taken in conjunction with the computerized master drawing file, this document defines all aspects of the M-C Power IMHEX® MCFC 250-kW stack design.

2.5.2 Complete Final Design and Procurement of Stack Non-repeat Components

The DCD, together with the computerized master drawing file, contains complete details on the non-repeat components necessary for the successful operation of the facility.

These non-repeat components include:

- ▶ Pressure vessel
- ▶ Pressure vessel internal piping and wiring
- ▶ Power module insulation
- ▶ Power take-offs
- ▶ Electrical isolation
- ▶ Stack instrumentation
- ▶ Guard heaters
- ▶ Insulation plates
- ▶ Clamping system (tie rods, bellows, load plates, etc.)
- ▶ Plenum chamber, with integrated anode end plate
- ▶ Cathode end plate
- ▶ Upper and lower insulator blocks

Each of these areas required significant engineering, design review, and procurement activities. The details of each of these components is not repeated here because those details are well documented in the DCD and the computerized master drawing file.

This task included the design of the pressure vessel, stack/pressure vessel insulation system, fuel cell end plates, plenum, top clamp plate, tie rods, isolation (electrical) block, DC power bus and the bellows which supply the clamping force on the stack. Nearly all of these components are of a custom design and fabricated in accordance with M-C Power drawings and specifications. The anode end plate and gas manifolding requirements were integrated into a single unit called a box plenum. The plenum is a box configuration made of 316 stainless steel, having four main flange connections for the reactant gases — anode in and out, cathode in and out. Internal baffling channels the reactant gases into and out of the MCFC stack's internal manifolds.

The active cell components or packages (repeat parts) are stacked upon the plenum which incorporates the anode end plate. The cathode end plate, made from 316 stainless steel was then placed on top of the stack. Above the cathode end plate is an insulator block. Above the insulator block are the load plate, bellows, and finally the top clamp plate. The load plate and top clamp plate were made from stainless steel. The bellows are of a welded, low-profile design to reduce the overall height of the fuel cell unit. The tie-rods pass through the corners of the plenum and the top clamp plate to hold the assembly together, provide structural rigidity and permit the bellows to apply a clamping force to the stack when pressurized. The DC power bus was machined out of an alumina-strengthened copper. The power bus was primarily fabricated as solid bars. A short flexible strap allowed for movement of the cathode for the long-term shrinkage (compaction) of the fuel cell stack and for the anode for thermal expansion/contraction.

2.5.3 Procure Raw Materials and Supplies; Manufacture Repeat Components

The fabrication of components for the 250-kW Unocal stack was the first manufacturing run for M-C Power which exceeded 20 kW in size. This increased manufacturing demand meant that

the raw materials logistics, production line staffing, equipment maintenance, process capabilities, operations sheet definition, quality control, and fabrication schedule conformance would be critically tested. In most cases it became evident that the fabrication of the components in large batch sizes would necessitate altering and adjusting the process and procedures to address fabrication issues that were previously unknown.

Wherever possible, statistical methods, including such techniques as multi-variant analysis (MVA), process capability studies, and production control charts were employed to minimize the non-recurring costs associated with the resolution of the particular issues and to minimize the implementation time of the required solutions. Operation sheets were written and included detailed instructions to the manufacturing technicians so that procedural variability induced during the manufacturing process could be minimized. These were coordinated with the engineering specification requirements, and were placed under configuration management change control procedures. The generation and updating of the operation sheets was a significant task in light of the first-time manufacture of large quantities of repeat parts.

Production staffing and assignments were adjusted to achieve a two-shift mixing and tape casting capability, a three-shift sintering capability, and a two-shift die-punching capability. Procedures were developed to maximize process throughput, while minimizing work-in-process inventory. Unfortunately, with the many issues to be resolved during the first-time, large-scale manufacturing activities, the minimization of process inventories was not effectively achieved until near the end of the Unocal fabrication run. The impact that this had on the production experience was to decrease process yields, as "downstream" problems could not be identified in a timely manner. Additionally, when a problem was discovered, it usually involved large numbers of parts.

M-C Power files and the DCD contain the details associated with the confirmation and verification testing of the Unocal cell components (100 cm² tests of electrodes from the manufacturing line); the bill of material (BOM) stack element drawings that were generated to support manufacturing activities; the costs associated with the Unocal stack fabrication process at M-C Power; and the listing of major program accomplishments which were documented for record during the course of the development activities. Similarly, the items documented in Section 5.1.1, Active Component Scale-Up, of this document feed into this effort.

2.5.3.1 Order Raw Materials and Supplies

In the transition from small scale, short run manufacturing to full scale batch manufacturing, large quantities of raw materials were ordered. To correctly manage these materials, a Materials Requirements Planning (MRP) System was established during the Unocal project. The MRP system development consisted of

1. Determining requirements of finished products, the master production schedule, from current contract forecasts.

2. Using the BOM, calculating the gross requirements for each item, beginning with the item at level zero.
3. Determining, using the BOM file and the inventory master file, the order release dates and the order quantities for each item necessary to meet the master production schedule.
4. Regeneration of the MRP on the basis of changes in the master production schedule in order priorities.

Once established, this information was then incorporated into a computerized MRP program. Based upon the calculated usage rates, the MRP system is capable of automatically deducting material quantities consumed on a per cast basis to give ending inventories. This information is then utilized to determine material reorder schedules and quantities.

2.5.3.2 Fabricate Active Components

2.5.3.2.1 Electrodes

Full scale manufacturing of electrodes began in January 1993 and concluded March 1994. A summary of electrode manufacturing through sintering is presented in Table 2.5.3.2-1.

**Table 2.5.3.2-1
Electrode Manufacturing**

TYPE	TOTAL	ACCEPTED	REJECTED	YIELD (%)
Anode	585	306	279	52.3
Cathode	412	279	133	67.7

During the Unocal project, the electrode manufacturing capacity was increased from short runs of 8 tapes per cast from a ten gallon mixer up to 30 tapes per cast using a fifty gallon mixer. Total manufactured quantities increased from 50 components to 500 components per each electrode type. To accommodate the increase in capacity, manufacturing schedules were increased from two shifts per day, eight hours per shift, five days per week, to three shifts per day, five days per week.

To insure repeatability and reproducibility (R & R) of mixes and casts, operation sheets were developed and implemented. To improve cross training and assignment flexibility, each operator was trained to follow these procedures.

As production increased, so did the degree and level of process inspection and control that was required. Visual inspection standards (attributes) and dimensional (variables) requirements were also agreed upon during this Unocal effort. Run charts were then implemented to monitor individual

and average component thickness, density and porosity and were used to determine process capabilities. Each cast tape was 100% inspected for both attributes (holes, cracks, etc.) and variables (thickness, % porosity, etc.). Defect data was recorded on a per tape basis. Defects found during tape casting did not necessarily create a defective part and as such those parts were transferred to the sintering room for sintering. To best control the total quality of parts from the mixing process through sintering, a production 'pull' theory was used to balance the line between tape casting and sintering. Tape casting lot quantities were based upon the quantity of parts that could be processed through the furnace. This minimized the amount of work-in-process (WIP) between the two operations. To maximize yields, variables were either eliminated or controlled. A multi-variate analysis was performed to identify man, machine, method, materials and environmental variables and their effects on the process. The greatest sources of variation in mixing and tape casting were formulation, repeatability between operators, mixing blade speed, tape caster doctor blade set up, and temperature.

The major sources of electrode sintering problems were the incomplete binder burnout of cathodes, metallurgical inclusions within the anodes and variations in porosity.

A root cause analysis and design of experimentation approach was employed to identify the sources of these variations in the electrode fabrication process. Minor retrofit design and processing parameter changes were then implemented to eliminate the root causes and bring the process into control.

Please refer to Section 5.1.1, Active Component Scaleup, which describes details associated with the definition and resolution of the electrode fabrication system.

2.5.3.2.2 Electrolyte Matrix

Electrolyte matrix manufacturing began September 1993 and ended April 1994. The manufacturing yield was 71.8%.

During the Unocal project, matrix and electrolyte manufacturing capacity was increased from short runs of 15 tapes per cast from a ten gallon mixer, up to 60 tapes per cast using a fifty gallon mixer. To accommodate the increase in capacity, manufacturing schedules were increased from two shifts per day, eight hours per shift, five days per week to three shifts per day.

As in the case of electrode manufacturing, operation sheets were developed and implemented to ensure R & R; and each operator was trained to follow these procedures.

As was also done with electrodes, visual inspection standards, attributes, and dimensional variable requirements were agreed upon. Run charts were then implemented to monitor individual and average component thickness, density and porosity and were used to determine process capabilities. Each cast tape was 100% inspected for both attributes (holes, cracks, etc.) and variables (thickness, % porosity, etc.). Defect data was recorded on a per tape basis. The greatest sources of

electrolyte matrix defects and breakage were tape brittleness, pinholes, lines, inclusions, and poor release.

Tape brittleness caused cracking during release and especially cutting. To remedy this situation, future casts will have a higher plasticizer percentage, and the parts will be stored in humidity resistant bags immediately after casting.

Pinholes were reduced/eliminated by changing mixing speeds to reduce "bubbling" of the mix and by the addition of an anti-foaming agent. Lines were reduced by increasing the belt tension and by taking greater care during belt rewind. Inclusions were reduced by modifying the milling times, more frequent replacement of the mill media and by doctor blade cleaning procedures.

Tape release was significantly improved by modifying the tape caster temperature profile to increase the drying rate to facilitate separation from the belt.

The matrix formulation was also changed to eliminate rolling. Prior to the Unocal production runs, all matrices were rolled to compact and flatten the tapes. The new formulation produced cast tapes which were flatter and of more consistent porosity. The deletion of roll compacting eliminated a very labor-intensive operation which required very high cost and high maintenance equipment.

The cutting of electrolyte matrix tapes was brought in-house. In-house cutting reduced the time to cut the parts by 66%. Prior to the Unocal production runs, electrolyte matrix tapes were packaged and shipped to a cutting vendor. Scheduling of the equipment and control of the process was severely limited. Vertically integrating this process significantly improved the quality of the process and the product and reduced the total operational costs.

Long term storage, 9 to 12 months, of both uncut and cut electrolyte and matrix tapes is now possible with vapor barrier bags. Sealed bags are then returned to the dry room until assembly.

Please refer to Section 5.1.1, Active Component Scale-Up, which describes the generation of electrolyte matrix manufacturing specifications and requirements.

2.5.3.3 Fabricate Separator Plates and Current Collectors

Each step in the manufacture of the separator plates and current collectors was performed by an outside vendor. The procedures followed for the in-house manufacture of the active components were followed by the vendor. The following individual production processes were monitored and supervised by M-C Power engineers, as documented in Section 5.1.2, Design, Engineering and Manufacture of IMHEX® Separator Plate, of this document.

- ▶ Acquisition of Ni coated 316 Stainless Steel
- ▶ Shipment to the pressing vendor
- ▶ Pressing

- ▶ Shipment of pressed parts to M-C Power in Burr Ridge
- ▶ Cutting and welding
- ▶ Cleaning and masking
- ▶ Aluminizing and annealing
- ▶ Final measurement and QC,

2.5.4 Stack Assembly

2.5.4.1 Mockup Testing

The objectives of the mockup tests were the evaluation of stack sealing with the new feed rail design and verification of a new electrode/wet seal fit up.

Two methods were employed for evaluation of stack sealing. In the first method, the extent of sealing was indirectly assessed by evaluating the local pressure on the wet seal rails as an indication of sealing. A pressure measuring film and screens were used to indicate the areas with sufficient local sealing pressure. When pressure was applied, the film discolored in varying shades of red, and the color density indicated the amount of contact pressure. Because the lower limit of the film sensitivity was relatively high (≈ 28 psi or ≈ 193 kPa), screens were used to detect areas with lower pressure. The screens could make an imprint on the matrix at pressures as low as 10 psi. A crossover test was another method for the evaluation of sealing.

Several mockups with differing numbers of cells were assembled and tested. Each cell in the mockups included all the metallic components of a real cell (anode, anode current collector, bipolar plate, cathode, and cathode current collector).

The pressure measuring film showed non-uniform pressure distribution over the active area. Regions of high contact pressure existed in the middle of the active area, especially near both non-manifold sides, and very small or no pressure was noted between the manifolds. The pressure over the wet seal area was also non-uniform. The pictures showed areas of little or no contact at the T-junctions between manifolds and at places where the blocking rails curve. The imprints from the screens confirmed this pattern of pressure distribution in other cells.

Several crossover tests were carried out to quantify sealing. During these tests, N_2 and CO_2 were supplied to opposite manifolds and GC analysis of outlet gases showed the extent of communication between the sides.

2.5.4.2 Repetitive Component Assembly

The repetitive component assembly includes two major steps: metal components assembly and stack assembly.

2.5.4.2.1 Metallic Components Sub-Assembly

The metallic components sub-assembly consists of the cathode half-cell and the adjacent anode half-cell which includes the following operations:

- ▶ Place the separator plate on the assembly table with the cathode side up.
- ▶ Place adhesive on the top surface of the ribs.
- ▶ Place a cathode current collector onto the plate and press it against the adhesive.
- ▶ Place a cathode on top of the current collector.
- ▶ Secure the cathode to the plate with adhesive.
- ▶ Turn the plate over and place it on the assembly table with the anode side up.
- ▶ Place an anode current collector on the plate.
- ▶ Place an anode on the top of the current collector and secure it to the plate with adhesive.

2.5.4.2.2 Stack Assembly

The stack assembly consisted of placing the white components on the anode end plate, adding the first metallic subassembly, and then the repetitive operations of placement of white components/installation of separator plates, and finally the installation of the cathode end plate.

The stack was assembled in the "dry room" (or the room with controlled low-humidity) at the M-C Power facility in Burr Ridge, Illinois. The stack was constructed on an "air cart," a device for transporting the stack from the dry room to the ATF for conditioning and testing. The air cart operates much like a "hover craft," supporting the load on a curtain of air while the assembly is moved.

The stack assembly started with the bottom cell — Cell No. 1. An anode current collector and an anode were placed onto the anode end plate. Then the electrolyte matrix was put on the top of the anode and aligned with the wet seal rails.

The next step was assembly of a separator plate with electrolyte matrix. This operation was repeated for each separator plate.

The overall alignment of the stack was controlled by the use of hard tooling columns.

The placement of each separator/cell subassembly was facilitated by a tool (spider) which was designed as described in Section 3.4, Fabricate Full-Area and Full-Height Stack Assembly Rig, of this document. Specifically, the spider would lift a fully assembled separator plate including white components on top of the electrode/current collector and place it on the white components of the previous separator plate. Then the next plate was assembled and the process was repeated up to plate No. 249.

The cathode end plate, pre-assembled with a cathode current collector and a cathode, was lifted by the hoist and placed on the top of the stack. A special fixture was used for the cathode end-plate alignment.

2.5.4.3 Non-Repetitive Component Assembly

An insulation plate, consisting of four equal pieces, was placed on the top of the cathode end plate, to insulate it electrically from the clamping structure. A stainless steel load plate was placed on the insulating plate. Six bellows, to provide a compressive force on the stack, were set on the load plate. Finally, the top clamping plate was placed on the bellows. The tie-rods, connecting the plenum with the top clamp plate and forming the clamping device, were then installed.

2.5.4.4 Stack Sealing

After the stack was assembled, several gaps were noticeable. Three gaps were located at the cathode end plate and three others were at the anode end plate. The location of the gaps at the anode end plate was at the manifolds C2, C4, and C5; at the cathode end plate, the gaps were at A2, A4, and A5. The largest gap was located at manifold A2 at the top of the stack. All other gaps were much smaller.

Attempts were made to close the gaps by alternately increasing and reducing the clamping pressure, by changing gas pressure to the bellows. The pressure cycles were repeated twice but the gap at manifold A2 did not disappear.

The top of the stack was disassembled and the wet seal rails of the cathode end plate were built up with the electrolyte matrix paste. Then the top of the stack was assembled again. This time no visible gaps were apparent. In the dry room, a "gas-flowing" seal test was developed to assess the readiness of the stack for conditioning. The data from this procedure indicated at the manifold pressure differences anticipated during the first stack heatup, 4 inches (10 cm) water column (w.c.), the external leakage would be about 1% of the total flow; therefore the stack was allowed to leave the dry room and begin conditioning.

2.5.4.5 Leak/Crossover Test

The purpose of this leak/crossover test was to quantify the quality of the stack sealing after conditioning and before the stack was shipped to Brea, California.

The test consisted of three room temperature steps:

Step 1: Gas was supplied to the anode inlet nozzle of the plenum and developed a pressure because the anode outlet nozzle was sealed, and both cathode nozzles were open. A measured gas flow (Flow-1) was equal to leaks from anode side to cathode side and from anode side to atmosphere.

Step 2: Gas was supplied to one of the cathode nozzles while the other was closed, and both anode nozzles were open. A measured gas flow was equal to leaks from cathode side to anode side and from cathode side to atmosphere (Flow-2).

Step 3: Gas was supplied to anode and cathode inlet nozzles while the outlet nozzles were sealed. A measured flow was equal to leaks from anode side and from cathode side to atmosphere (Flow-3).

Knowing Flow-1, Flow-2, and Flow-3, it was possible to calculate separately the leaks from anode side to cathode side, from anode side to atmosphere, and from cathode side to atmosphere. As discussed later, the stack developed communication between anode and cathode manifolds after electrolyte melting. This was confirmed during post ATF disassembly. The gaps originally observed at room temperature in the dry room reappeared. This was especially true at the cathode endplate/A2 and anode endplate/C2. All gaps were pasted with electrolyte matrix cement. Then this "static" gas sealing test was conducted prior to shipment to Brea, California. The data indicated that the leakage from anode to cathode, from anode to atmosphere, and from cathode to atmosphere, were all in the order of 0.1 to 0.3 slm/cell (0.003 to 0.01 scfm). At this time, these low leak rates were judged acceptable.

Λ
/cell

2.5.5 Stack Conditioning

Stack conditioning included three major phases: binder removal, electrolyte melting, and cathode oxidation. This stack was to be subjected to gas recycle for the first time during stack conditioning; all of the shorter stacks employed once-through gas flow for this step.

The stack conditioning was accomplished in the ATF. The ATF is an atmospheric pressure facility that can provide hot, metered gases to both anode and cathode manifolds of the stack, while simultaneously providing for recovery of spent binder. It also included a mechanism for compensating for the dimensional changes that the stack undergoes during conditioning. The design and construction of the ATF is discussed in Section 4.0 of this document.

The stack was transported to the ATF on the air cart, and the stack flanges were connected to the facility piping for stack conditioning.

2.5.5.1 Binder Removal

The gas flows and the heatup schedule were chosen based on previous stack testing experience and results of binder removal studies performed in several bench-scale cells.

The binder removal process was monitored continuously by Model 400A Hydrocarbon Analyzers. Each side (anode and cathode) had two analyzers on line. One was located downstream of the stack but before the carbon beds, and another was located immediately after the carbon beds. The first analyzers displayed the rate of binder removal. The second analyzers showed the effectiveness of the carbon beds. The maximum readings of these second analyzers were always under 80 ppm, even when the first analyzer registered > 3000 ppm level. These readings were verification of the effectiveness of the carbon beds.

To ensure a uniform binder removal, some temperature constraints were employed as guidelines. The allowable maximum difference between temperatures within any one cell was set to 20°C. This goal was met during the binder removal period. Figure 2.5-1 presents the vertical temperature distribution in the stack during binder removal.

2.5.5.2 Electrolyte Melting

The technique of controlled electrolyte melting during the Unocal stack conditioning was generally considered to be a serious issue. The potential existed for possible stack failure during the electrolyte melting process:

- ▶ Non-uniformity of melting could develop a tilt, which, in turn would cause a side force to shift the plates.
- ▶ Regardless of what heating procedure was chosen, the carbonate around manifolds would melt before the remainder of the active area region. This phenomenon meant that for some period of time, the stack could lose sealing forces and become open to the atmosphere.
- ▶ If, at that time, air would enter the stack, the nickel electrodes would oxidize. Because of the exothermic character of the nickel oxidation reaction and the considerable heat evolution, the melting would occur very quickly and even more non-uniformity. That effect could lead to the failure mode mentioned above.

The approach chosen was to develop a procedure which would allow the electrolyte in the stack to melt from the top of the stack, downward at a controlled rate. This technique would keep the number of cells with melted wet seals and solid active areas to a minimum.

UNOCAL 250 kW STACK VERTICAL TEMPERATURE DISTRIBUTION DURING BINDER REMOVAL

Figure 2.5-1 Vertical Temperature Distribution During Binder Removal

A study of a heating procedure was performed to determine if the stack, during the electrolyte melting process, could be brought down in a controlled manner with the aid of electric heater control. Consideration was given to using heater control to minimize the rate of stack height change. A two-dimensional finite element model of the 250-cell stack was used for the analysis. Heat transfer was simulated by both radiation and conduction from the heaters to the stack perimeter rail area. Radiation and conduction were also included between the perimeter rail and the active area through the manifold region.

The transient heat transfer analysis results indicated that the number of cells with melted perimeter and solid active areas could be maintained at 20 and 50 over the course of melting. A heating schedule was developed which could be used as a reference for the actual melting process.

To eliminate the possibility of uncontrolled electrode oxidation during the melting, a nitrogen purge was used within the stack furnace enclosure. The composition of the enclosure atmosphere was periodically monitored during melting with GC-analysis and confirmed to contain less than 2,000 ppm O_2 .

The gas flows were made equal for both sides of the stack to protect the wet seals and to provide uniform heat transfer. This was the only time when anode and cathode flows were equal. The anode and the cathode gas heaters and the furnace enclosure heater for the bottom zone were set to maintain the gas inlet temperature below the melting point.

During melting, special attention was paid to the stack tilt and the temperature distribution. Four LVDTs provided continuous information on stack displacement. The stack tilt was calculated periodically using the LVDT data. The stack shrinkage was monitored using a string potentiometer and by the cumulative movement of the clamping device.

Figures 2.5-2 and 2.5-3 illustrate the horizontal and vertical temperature distributions in the stack during electrolyte melting.

2.5.5.3 Cathode Oxidation

In preparation for cathode oxidation, the gas flows were changed. Hydrogen and steam were added to the anode gas and carbon dioxide was added to the cathode gas. When the temperature in the stack reached $\approx 580^\circ C$, a small amount of air was added to the cathode gas. During cathode oxidation, the air flow was increased in small increments to prevent excessive temperature rise and provide reasonable temperature control. The highest temperature in the stack during cathode oxidation was below $650^\circ C$.

The process of oxidation was monitored by internal stack temperatures and cell group voltages. The voltages were read for groups of 5 cells and the average cell voltages were then calculated from the readings. Figure 2.5-4 demonstrates the temperature changes in a cell during cathode oxidation.

UNOCAL 250 kW STACK

Cell One Temperatures During Melting

Horizontal Temperature Distribution

Figure 2.5-2 Horizontal Temperature Distribution During Electrolyte Melting

UNOCAL 250 kW STACK VERTICAL TEMPERATURE DISTRIBUTION DURING ELECTROLYTE MELTING

Figure 2.5-3 Vertical Temperature Distribution During Electrolyte Melting

UNOCAL 250 kW STACK CELL TEMPERATURES CELL 75 DURING CATHODE OXIDATION

Figure 2.5-4 Cell Temperature During Cathode Oxidation

During cathode oxidation it was discovered that, defective electrical insulation caused some of the voltage leads to short-circuit to the metal floor and to each other. This problem was corrected outside the enclosure, but there were also short circuits on the stack inside the enclosure. Nothing could be done at that time, and stack conditioning was continued.

2.5.5.4 Acceptance Test

The acceptance test included a leak test, open-circuit voltage (OCV) measurements, and stack operation at 400 A.

2.5.5.4.1 Leak Test

At the completion of cathode oxidation, a leak test was performed to check stack sealing. Flows during the leak test were the same as the flows needed for OCV except there was no CO₂ in the anode gas because CO₂ was used as an indicator of crossover. The flows were:

<u>Anode flows</u>		<u>Cathode flows</u>	
H ₂	790 slm (28 scfm)	Air	2400 slm (85 scfm)
N ₂	790 slm (28 scfm)	CO ₂	1200 slm (42 scfm)
H ₂ O	490 slm (17 scfm)	N ₂	1200 slm (42 scfm)
Recycle	3000 slm (106 scfm)	Recycle	14000 slm (494 scfm)

The pressures in the stack were adjusted so the cathode outlet pressure was slightly above the anode inlet pressure. GC-analysis was performed on all anode manifolds. CO₂ was detected in all anode manifolds indicating communication between the anode and cathode gases.

The GC-analysis results from the A2 manifold at the cathode end plate differed significantly from those at the other manifolds. After cathode oxidation, pressure readings in the manifold were zero. Post-test visual inspection of the area indicated a loss of the outer wet seal at A2 in Cell 250.

2.5.5.4.2 Open Circuit Voltage

OCV data were collected several times at different gas compositions. The anode and cathode flows were set for operation at 400 A, and cell group voltages were measured both with and without anode gas recycle. The voltages of groups consisting of five cells each were measured and the group average and the cell average were calculated from these measurements. In the cases where there were short circuits, voltages were measured for groups of ten cells. Figure 2.5-5 presents the average cell voltage for each group of five cells. For the whole stack, the average cell voltage was 1.077 V. The calculated OCV was 1.075 V, showing good agreement.

2.5.5.4.3 Performance Test

The Unocal stack was loaded with 100 A, 200 A, and 400 A. Anode flows were set for operation with 50% fuel utilization at 400 A without recycle. Recycle was used only for cathode

Figure 2.5-5 Open Circuit Voltages of Cell Groups

Unocal Stack Performance Average Cell Open Circuit Voltages

gas. The fresh cathode gas had composition 70% air - 30% CO₂ but, because of the recycle (nitrogen accumulation) and the limited air and CO₂ flows (the ATF equipment limits) the oxidant was diluted and cathode O₂ and CO₂ utilizations were $\geq 50\%$. The maximum stack power output was 82 kW.

Figure 2.5-6 illustrates the stack performance with anode flows set for 50% fuel utilization at 400 A. Disregarding the voltage groups with obvious discrepancies, the mean cell potential at 400 A was 810 mV. Based on other testing data, it is known that when the stack matures, the potential will increase by about 50 mV; therefore, the anticipated performance of the Unocal stack at the ATF conditions would be 860 mV.

The voltage that would be expected, based on 20-cell stack tests and Nernst effects, is 894 mV. The difference may be explained by:

- ▶ Possibly higher internal resistance due to relaxation of the plates during electrolyte melting.
- ▶ The cumulative effects of stacking in which thinner component regions align and accumulate thin-on-thin, and similar situation with the thicker component regions leads to higher IR and lower integrity seals at the end of the stack.
- ▶ The effects of longer-term storage of some of the active components while awaiting stack assembly.
- ▶ The strain imposed upon the stack during efforts to flatten the system.
- ▶ The effects of generic electrolyte loading per cell as compared to specific matching.
- ▶ The impact of using current collectors of a single thickness rather than selecting current collectors of specific thicknesses to match the other dimensions in the cell.

2.5.6 Power Module Assembly

The power module assembly subtask included installation of the fuel cell stack into the pressure vessel along with all the pertinent accessories and instrumentation. This activity required approximately two weeks of intensive effort by M-C Power staff and several vendors. Assembly was accomplished using the sequence of activities described below.

The bottom of the pressure vessel arrived at the M-C Power facilities on a standard flat bed truck. It was transferred, using a crane, to the low-boy trailer which would be used for transport of the assembly to California. This low-boy trailer was of a special design, using 42 wheels on eleven axles, to handle the weight of the entire load. The stack was lifted with a crane, and placed into the

Figure 2.5-6 Cell Potentials Under Load in Acceptance Test Facility

Unocal Stack Performance Average Cell Voltages

bottom of the vessel. This trailer system was then moved into an indoor, level truck bay at M-C Power.

Once inside the truck bay, the plenum was securely anchored to the base of the vessel. The pipe spools (between the vessel wall and the plenum) were installed, and the gas piping connections, including ceramic isolation spacers at the plenum, were completed. Instrumentation routing and connections were completed next (some of which were started in parallel with previous activities). The instrumentation included routing tubing for MCFC manifold pressure taps, cables for voltage leads, thermocouples for temperature measurement in the fuel cell stack and for guard heater controls, cables for A.C. power to the guard heater, and installation of pressure vessel fittings to route instrumentation lines out of the vessel.

Next, the final D.C power bus bars were installed along with the flexible cable power straps. The guard heater and its associated supports and brackets was then placed around the stack. Panels were installed on the outside of the guard heater walls forming an insulation cocoon. The vessel floor, plenum, gas piping and vessel walls were covered with thermal insulation of varying materials and thicknesses to achieve a relatively cool void space between the insulation cocoon around the guard heater and the vessel wall.

Finally, wood bracing and cabling with turnbuckles were installed to secure the load for transportation. On the outside of the vessel, protection covers were installed onto the nozzles to prevent damage to the instrumentation leads and wiring. The day before shipment the top of the vessel was placed onto the bottom and securely bolted and the entire load secured to the truck.

2.6 Subtask 2.6 Power Plant System Test with Reformed Natural Gas

Objective:

To establish test goals, develop a power plant manual and operations plan, and conduct the 250-kW power plant test.

Discussion:

2.6.1 Development of Test and Operating Plans

A detailed test plan and operating program was developed with an assessment of data acquisition and analysis of the Unocal power plant.

2.6.1.1 Introduction

The test plan for the Unocal demonstration plant consisted of a 250-hour Process and Control (PAC) test and a 4,000-hour full-plant test.

In the PAC test, the stack was physically isolated from the rest of plant by blinding off all feed and effluent points and diverting flow through bypass lines. This is to verify the balance-of-plant performance and operability and to fine-tune the control system without damaging the fuel cell stack.

Upon successful completion of the PAC test, the fuel cell stack was connected for the full plant test. The major objectives of the full plant test were to demonstrate that:

- ▶ The 250-cell, full-area, commercial scale stack can operate properly in an integrated power plant environment.
- ▶ The stack can sustain prolonged operations without significant decay.
- ▶ The integrated power plant can smoothly and safely start-up, shutdown, and follow load changes.

Other, more specific objectives are as follows:

- ▶ To explore the maximum fuel utilization achievable in the stack.
- ▶ To verify the overall system dynamic responses and load-following characteristics.
- ▶ To confirm the stack pressure drops and overall system pressure profile.

- ▶ To establish the optimal set points for various operating parameters, such as vessel gas purge rate and bellows nitrogen operating pressure.
- ▶ To gain familiarity and operating experience with the balance-of-plant equipment for supporting the fuel cell stack.
- ▶ To obtain feedback on material selection, control logic, safety protection, skid layout, electrical design, piping and valve design, and civil and structural design to assist future design and development of commercial units.
- ▶ To verify the low emissions characteristics of fuel cell power plants.

In both the PAC test and full plant test, Unocal was responsible for the plant operation and data acquisition via the distributed control system (DCS), gas and water samples collection and analysis, and data transmission to other project members. M-C Power was responsible for the fuel cell stack data analysis. Bechtel was responsible for the overall system data analysis. M-C Power, Bechtel, and Stewart & Stevenson assisted Unocal with trouble shooting and provided operation and test guidance. Bechtel, with assistance from other project members, summarized the test results and documented the "lessons learned" as an internal report for use by the M-C Power team.

2.6.1.2 Data Acquisition

The instrument data which were automatically recorded by the DCS on a continuous basis include:

- ▶ Process and utility stream temperatures, pressures, and flowrates.
- ▶ Differential pressures between process streams.
- ▶ Voltage, current, and power output from the fuel cell stack and the inverter.
- ▶ Auxiliary power consumption including the voltage and current input to the gas blowers and electric heaters.
- ▶ Rotating speeds of the blowers and turbocharger.

Data were transferred and logged daily in a data acquisition system DAS which pulled specific data from the DCS on a continuous basis to be used for analysis. In addition to the above data acquisition, gas and water samples were periodically taken for analysis.

2.6.1.3 Component Performance Analysis

2.6.1.3.1 Desulfurizer

In the endurance test runs, the sulfur content in the natural gas feed was compared on a weekly basis with that in the desulfurized gas to detect any sulfur break-through. Similar analyses were performed on a monthly basis for the chlorine content to verify the chlorine removal effectiveness of the desulfurizers.

2.6.1.3.2 Reformer

Performance measurements were made to verify the following specifications and checks:

- ▶ Operability of the desired range of operation.
- ▶ Methane conversion, approach to equilibrium.
- ▶ Controls and instrumentation.
- ▶ Natural gas flow rate to the unit.

Heat and material balances were conducted to identify heat losses. The balance envelope was taken around the reformer excluding the exhaust heating coils.

2.6.1.3.3 Fuel Cell Stack

Material balances were performed to determine mass leaks across the fuel cell and a heat balance was conducted to determine heat losses. The balance envelope was taken around the fuel cell vessel. Composition samples were taken daily and therefore heat and material balances can be performed daily.

Gas crossover could occur from the fuel cell vessel (purge gas) to either the anode or the cathode or from the anode to the cathode. Flow rates of nitrogen in and out of the fuel cell vessel were used to diagnose leakage across the fuel cell wet seals.

The voltage, measured for every 5 cells was monitored for its degradation with time in the endurance tests (Runs 5, 13, 18, and 27 of the full-plant test matrix). The voltage distribution among cells was also analyzed.

2.6.1.3.4 Hot Gas Recycle Blower

The blower performance analysis included:

- ▶ Differential head versus blower speed.
- ▶ Flow rate versus blower speed.
- ▶ System pressure drop profile.

- ▶ Power draw versus blower speed.
- ▶ Overall efficiency versus blower speed.

During the system warm-up, these data were compared to the vendor-supplied blower curves.

2.6.1.3.5 Cathode and Anode Start-up Heaters

The heater performance monitoring included:

- ▶ Power input to the heaters.
- ▶ Operating temperatures of the heaters.
- ▶ Temperature controls.
- ▶ Operability of limit switches.

These heaters were used only during system warm-up in the PAC test and during start-up in the full plant test.

2.6.1.3.6 Catalytic Combustor

The catalytic combustor performance was measured at standby, 80% fuel utilization, and 60% fuel utilization. The performance was analyzed to:

- ▶ Verify hydrogen destruction efficiency.
- ▶ Verify methane destruction efficiency.
- ▶ Check controls and instrumentation.

2.6.1.3.7 Recycle Gas Steam Generator

The performance analysis of the steam generator included:

- ▶ Calculation of the overall heat transfer coefficient.
- ▶ Calculation of the cooling duty.
- ▶ Check of controls and instrumentation.
- ▶ Verification of gas side pressure drop.

2.6.1.3.8 Cool Gas Recycle Blower

The performance analysis of the recycle blower included:

- ▶ Differential head.
- ▶ System pressure drop profile.
- ▶ Flow rate.
- ▶ Power draw.
- ▶ Overall efficiency.

2.6.1.3.9 Turbocharger

The performance analysis included:

- ▶ Shaft speed.
- ▶ Compressor performance (head, flow rate, efficiency).
- ▶ Expander performance (pressure drop, flow rate, efficiency).

2.6.1.3.10 Control System

Throughout the PAC test, the control system was checked and the controllers were tuned. Proper operation of all alarm and automatic shutdown sequences were verified. In order to perform the PAC test, several signals were sent to the DCS via calibrated output devices to permit the system to simulate actual operating conditions.

2.6.1.3.11 Inverter

The inverter conversion efficiency was analyzed.

2.6.1.4 System Overall Performance Analysis

During the full plant test, the following overall system performance characteristics were studied, verified and documented:

- ▶ Overall electric efficiency (Natural gas HHV & net power produced and exported to Unocal).
- ▶ Cogeneration efficiency.
- ▶ Trends from previous runs to be used to adjust setpoints for next runs.
- ▶ The load response characteristics, such as cathode temperature change when load changes.
- ▶ Dynamic response of other equipment.
- ▶ Verification of start-up procedures to pressurize and heat up the system.
- ▶ System heat losses through vessels and pipes.
- ▶ Control logic operability for safety shutdown and ability to respond to emergencies.

2.6.1.5 Summary of Results and Reporting

Personal computer (PC) programs were developed to automatically calculate the heat and material balances and plant performance and to perform the trending. Most of the programs will be stored in the PC of the DAS.

Results of the data analysis were summarized in a Topical Report to the DOE.

2.6.2 Power Plant Operation

The 250-cell IMHEX[®] MCFC stack power module arrived at Brea from M-C Power in late November, 1994. It was unloaded, installed on its pad, and made ready for the formal dedication on December 2, 1994. The pressure vessel cap was then removed for dismantling of the transportation reinforcements. A triple layer tarp and weatherized plastic tent system was used to provide protection for the vessel interior.

During this time, an exceptionally rainy winter season began in southern California. Much of the next two weeks was devoted to drying external instrumentation fittings and eliminating short circuits caused by wet wiring, insulators, and tubing feeds. After the vessel was resealed, the site contained the control and electrical building, the S&S skid, the reformer, and the power module, with the stack in its vessel. Most of the BOP control valves, interconnecting piping, wiring, and instrumentation had yet to be installed. Further, the rains were so heavy that the mechanical and electrical work was often interrupted, especially when the jobsite would be under water.

2.6.2.1 Process and Control (PAC) Test

The facility was ready for the PAC test on March 2, 1995. The test required two months, because of numerous instrumentation and/or equipment failures, as outlined in Tables 2.6.2-1 and 2.6.2-2, respectively.

TABLE 2.6.2-1

SUMMARY
INSTRUMENTATION MODIFICATIONS

Instruments, that failed to operate properly, and were repaired or replaced:

- ▶ O₂ analyzer at the reformer bridgewall
- ▶ H₂ analyzer at the fuel cell purge line outlet
- ▶ O₂ analyzer at catalytic combustor
- ▶ O₂ analyzer at cathode exhaust line
- ▶ Flow sensor and transmitter for anode exhaust
- ▶ Flow indicator and transmitter for superheated steam
- ▶ Flow indicator and transmitter for 150 psig steam import/export
- ▶ Flow transmitter for N₂ to fuel cell purge line
- ▶ Flow transmitter for CO₂ to fuel cell purge line
- ▶ Valve regulating steam to the reformer
- ▶ Valve regulating reformat flow to stack
- ▶ Valve regulating steam to the steam superheater
- ▶ Pressure control valve for export steam from steam generator
- ▶ Controller for dP between anode inlet and cathode outlet
- ▶ dP indicator and transmitter for cooled gas recycle blower
- ▶ Valve for venting anode inlet gas
- ▶ Valves regulating pressures in the two sets of bellows
- ▶ Thermocouple in the catalytic combustor
- ▶ Valve for cooled recycle gas to the catalytic combustor
- ▶ Power bus fittings through the pressure vessel.
- ▶ Valve for the air to the catalytic combustor inlet
- ▶ Valve for the cooled recycle gas to the catalytic combustor inlet
- ▶ Power bus fittings through the pressure vessel

Even with the modifications listed above, the instrumentation reliability was an issue.

A lesson learned during the PAC test and facility operation was the need for data analysis programs, and operators trained in their use, for the reformer, the combustor, and the MCFC material-balanced system. Simply reading the instruments or the computer screen, even with immediate GC analyses, did not supply enough information to determine if the system was operating correctly.

TABLE 2.6.2-2

**SUMMARY
EQUIPMENT MODIFICATIONS**

Equipment, that failed to operate properly, was repaired, replaced, or removed from service:

- ▶ Catalytic combustor
- ▶ Steam generator
- ▶ Reformer
- ▶ Fuel cell guard heaters
- ▶ Induced draft fan for reformer combustion section
- ▶ Hot gas recycle blower
- ▶ Turbocharger - totally removed from the plant configuration
- ▶ Cool gas recycle blower
- ▶ Cathode start-up heater
- ▶ Anode start-up heater

The equipment failure that was the most time consuming was the reformer. This unit was supposed to be of standard design, just using fewer of the standard reformer tubes. Yet, the burner orifices were drilled out, debris was discovered in the convection section, gaps around the tubes had to be sealed to reduce air infiltration, and the burner was replaced. Still, at the end of the PAC test, the reformer could not operate at 100% capacity because the burner could not supply enough heat.

Similarly, the hot gas recycle blower shaft and casing seal failed several times. This blower was critical to the operation. It was the cause of test termination during the first operation of the stack. Bechtel and the blower vendor conducted an extensive re-design to improve blower reliability for future MCFC demonstrations. The PAC test was concluded on May 3, 1995.

2.6.3 Total System Operation

As previously mentioned, the PAC test was conducted with the MCFC stack *not* included in the system. Rather, pipe spool pieces were included to by-pass the stack on both the anode and cathode. To prepare for the actual plant start-up, these spool pieces were removed and other minor modifications were made.

The heat-up of the MCFC stack started on May 12, 1995. The recycle blower was operated and the valving was set so that the blower output was directed to both the anode and cathode inlets. The exhausts from the anode and cathode bed were fed back to the blower inlet. Prior to entering the MCFC vessel, both the anode and cathode feed lines passed through electric "start-up" heaters, which were operating to heat the recirculating gases and the stack. The gas in the recirculating loop was nitrogen.

On May 16, the heat-up rate had decreased to unsatisfactory levels. Further, the electric start-up heaters were being pushed to their limits. An additional source of heat was needed. It was decided to start the reformer and feed nitrogen and steam through the convection section and the reformer tubes and into the anode feed line to the fuel cell. This approach would add heat to the stack from the reformer.

All stack temperatures continued to increase during May 16 and the first half of May 17. The anode inlet temperature started to increase faster than the rest of the stack temperatures on May 17, indicating the skewed effect of the additional heat from the steam and nitrogen added to the anode inlet first. This effect required over 8 hours to manifest itself. During this same time period all four walls of the guard heater failed. This was due to a vent valve which was set open during startup for pressure balancing. This allowed steam from the cathode outlet to back flow into the vessel and attack the heater connection.

Throughout the day of May 17 all of the temperatures in the bottom end plate continued to rise, with the anode inlet manifold temperatures rising faster than the anode outlet manifolds. At about midnight, the anode outlet manifold temperatures stopped increasing. The relatively stable outlet manifold temperature was the usual manifestation of electrolyte melting. This indicated that the anode inlet region of the cell was being "driven" through melting while the outlet portion was taking in heat at a slower rate, consistent with salt phase change.

Up to this time, the MCFC stack had not yet been fed fuel or oxidant.

At about noon on May 18, reformer operation was started to provide fuel for the MCFC. The anode exhaust, at open circuit, was fed to the combustor which ignited with air and fed a stream of about 7% oxygen concentration into the recirculating cathode stream.

A sensitive thermal set-point caused "trips" of the system, closing the valve between the reformer and the stack and, almost immediately, closing the valve feeding air to the combustor. These system trips caused significant pressure pulses of up to 80 inches w.c. At least 3 trips of the system were recorded. When the trip initiated valve closure, the system still had fuel and oxidant in the stack; however, fresh feed was temporarily stopped.

At 1815 hours, on May 18, 1995 the inverter was turned on and power was exported to the grid.

It was recognized that the stack was still colder than design temperatures, although generating this power still caused an increase in the outlet manifold temperatures, and that the flows and delta-P's were erratic and needed tuning. At this time, temperatures in the exhaust manifolds were still in the thermal arrest phase which is characteristic of electrolyte phase change. In retrospect, improper vendor calibration range specifications on thermocouple field signal conditioners yielded artificially high temperature readings which masked the extent to which the stack temperatures were actually off-design and cool.

The stack operated continuously at a 40 A load for over 12 hours between May 18 and May 19, when the reformer was tripped by feeding nitrogen into the reformer in an attempt to get more mass into the anode stream. The stack was operated for two more hours. The stack was getting warmer, but the voltages were not improving. Most exhaust manifold temperatures had climbed to the region of normal operation, but the stack performance did not improve. With the fuel and oxidant being fed to the stack, it should have been producing about 400 A at about 200 V. Instead, it was producing 40 A at about 165 V.

Thirty five hours after initiating load, gas samples were drawn. The mass spectrometer data indicated a low, 4% nitrogen crossover and outlet gas composition consistent with the flows and load.

On May 20, experiments were run by increasing the CO₂ and/or O₂ concentrations in the cathode feed, with only minimal voltage improvement. The current was increased in steps and the stack ran overnight at 68 A and 166 V (11.3 kW). The cathode inlet manifold pressure was 25 to 40 inches w.c. higher than the anode outlet pressure, indicating severe stress on the wet seals of the stack.

The stack continued to operate on May 21 with planned evaluation of manifold pressures and vessel pressures. When both recycle blowers failed, the first phase of the test was terminated. The system was cooled for maintenance, and the vessel head was removed on May 31, 1995.

The following work was completed: two recycle blowers were repaired; the vessel floor insulation was replaced; patches of steam-scorched vessel wall insulation was replaced; the guard heater was re-insulated, refurbished and re-wired; voltage leads were removed, re-routed, re-welded; stack pressure tap fittings were replaced or re-welded; stack observations, dimensional measurements, cell resistances, and Megger measurements; all stack temperatures, pressure and voltage signal conditioners were recalibrated and DCS readouts confirmed; power bus joints refurbished; clamping device bellows tubing and valving was troubleshot; developed a Startup Plan Chart; created, within the DCS, a family of trend charts for use during startup and operations; and LVDT's were re-calibrated and installed. Heat-up was started, under N₂ atmosphere, on June 16, 1995. The manifold temperatures in the lower end plate were about 1000°F (except for the cool anode feed gases) and those in the upper end plate were hotter yet when reformat was added to the stack on June 29, 1995. Temperatures and gas compositions were allowed to stabilize for a day and the open circuit voltage reached 233 V, 932 mV per cell, which compared favorably with the theoretical voltage at those conditions of 936 mV. An attempt to draw load on June 30 was unsuccessful. The stack could not deliver the 30 amps required to activate the inverter. A similar effort on July 1 was also unsuccessful, so the second heat-up was terminated.

2.7 Subtask 2.7 Integrate Demonstration Test Results into Power Plant Design

Objective:

To integrate the results of the power plant test into strategies, schedules, and full-scale power plant project formation and into the field test program and commercial power plant offerings and configurations.

Discussion:

The results of this subtask are summarized in the two Topical Reports discussed below.

2.7.1 Lessons Learned

One of the major outgrowths of a project such as this is the accumulation of "lessons learned." The lessons learned are summarized in a Topical Report on the Subject. These lessons can be factored into the design of the next effort, for improved strategies, schedules, and full-scale power plant project design and operation efforts.

2.7.2 Failure Analysis

Generally, in a failure analysis, the investigating team can find a "root cause." In this case, however, many causes contributed to the failure of the Unocal stack to perform according to expectations. The major causes are discussed below. They are listed temporally, rather than in order of criticality, because the time factor also helps to explain the overall loss. Many minor causes were also contributory to the overall poor performance, however, they are not as critical.

- ▶ Lack of experience in stacking stacks taller than 20 cells and operating them integrated with more traditional power plant equipment.
- Issues regarding stacking tall stacks: stacking up patterns of thicknesses. Each of the 2500 components of the stack had variances in physical dimensions. These variances were not random. Rather, the same location on a component would be consistently thick or thin. This effect would impact the stacking whether the variance were temporary (e.g., electrolyte matrix tapes or component adhesive) or permanent (e.g., the separator plate was slightly thicker along the short edges). A difference of 3 mils (i.e., from component adhesive) per plate is additive to 0.75 inches when 250 cells are stacked. Significant effort was expended, and stress applied to the stack, in attempts to flatten the stack to counteract this type of effect.
- ▶ The effects noted above also became apparent when the residual internal stresses in the separator plates became assertive with time. Again, during electrolyte melting, the plates can relax and rest, thus affecting the stack flatness and seal integrity.

- ▶ Events prior to the final enclosure of the stack in mid-January included loss of nitrogen pressure at least four times. Without the nitrogen pressure, the force within the MCFC bellows systems would be lost and the axial clamping force on the stack would be lost. The innate spring nature of the stack, like 250 Belleville washers, would tend to open up the stack sealing. Upon re-melt, the corrugated separator plates would not align perfectly and re-contact non-oxidized surfaces on the current collectors, and the stack internal resistance would be increased.
- ▶ Heat losses from the MCFC system at Unocal were high. The start-up heaters were under-sized and the 2-stage catalytic combustor was not designed for supplemental firing. In other words, insufficient heat was available during start-up to realize an acceptable heat-up rate.
- ▶ The use of N_2/H_2O , heated by the reformer, as a supplemental heat source for the stack was probably undesirable. A failure analysis bench scale test indicated that 35% of the performance loss at Unocal is explained when a conditioned cell is reheated in either a nitrogen or a steam and nitrogen atmosphere.
- ▶ During preferential (from the anode inlet side) remelt, the stack tilted and gaps opened on the cathode inlet side. Pressure surges resulted from controller "trips" as the fuel and/or air feed to the stack was shut off. It is possible that oxidant from the cathode inlet manifold could have entered the anode compartments and reacted with the nickel anodes.

The absolute root cause of the stack failure has not been determined, but is believed to be a combination of the factors listed above. A detailed discussion on the subject is covered in a separate "Test Analyses Report" for use by the M-C Power team.

3. TASK 3. MANUFACTURING FACILITIES DEVELOPMENT

The objective of this task was to address issues impeding development of manufacturing facilities to support MCFC stack research and power plant development.

3.1 Subtask 3.1 Maintain Tape Casting Machine and Sintering Furnace

Objective:

To develop a procedure and plan to properly maintain the government-owned tape casting machine and sintering furnace located at M-C Power's facility and to modify these machines as required to improve capabilities, quality, and production rates.

Discussion:

3.1.1 Maintenance of Equipment

3.1.1.1 Tape Casting

- ▶ Developed schedules for the preventive maintenance (PM) of the tape casting equipment.
- ▶ Completed PM monthly, quarterly, and yearly as needed, in accordance with the schedules developed above.

3.1.1.2 Sintering Furnace

- ▶ Developed schedules for the PM of the sintering furnace, including periodic shortening of the continuous wire mesh belt and tracking adjustments.
- ▶ Completed periodic PM monthly, quarterly, and yearly as needed, in accordance with the schedules developed above. Completed periodic tracking adjustments of the continuous wire mesh belt.

3.1.2 Improvement of Manufacturing Equipment

3.1.2.1 Tape Casting

The following improvements were made to the tape casting and mixing areas during the Unocal development and production effort:

- ▶ Second tape caster installed.
- ▶ Mixing room modified to incorporate larger (50 gal.) mixers.
- ▶ Completed installation of 50 gallon mixers.
- ▶ New take off wedge designed, manufactured and installed.
- ▶ Take-off temperature controllers designed and installed to facilitate release.
- ▶ Added an anti-static 'air knife' to take-off end to eliminate/reduce chips and to improve release.
- ▶ Fabricated and installed carbon bed platforms above tape casters to accommodate two tape casters.

3.1.2.2 Sintering Furnace

The following improvements were made to the sintering furnace during the Unocal development and production effort.

- ▶ Installed quick change entry door transition wedge.
- ▶ Installed pre-heat section gas treatment system.
- ▶ Received new pre-heat section muffle.

3.1.2.3 Component Inspection Equipment

- ▶ Relocated thickness mapping and weight scale from tape casting room to warehouse area to improve product flow.

3.2 Subtask 3.2 Develop Quality Assurance (QA) Procedures and Laboratory

Objective:

To develop and implement quality assurance and quality control procedures and plans to assure the quality of the electrochemically active MCFC components produced at M-C Power's facilities. For this purpose, M-C Power will complete equipping its QC Laboratory and select analytical service vendors to provide the required quality control support. In addition, M-C Power will construct a single cell test facility to assist in establishing component quality assurance and quality control.

Discussion:

The initial emphasis was on the development of test methods as a means of identifying critical characteristics requiring improvement, determining those processes affecting these characteristics, and using the test data generated to gauge quality improvements. Because of the developmental nature of many operations, the true requirements for subcomponents to achieve overall stack performance and life criteria were not known. As a result, it was necessary to first develop valid test and inspection methods to assess the quality of stack components and, through the evaluation of post-test materials, feed this information back for continuous improvement.

3.2.1 Quality Control Procedures

3.2.1.1 Test and Measurement Procedures

Procedures for component measurement were developed, validated, and documented. Approximately twenty test procedures were developed primarily dealing with the measurement of bipolar components and assemblies. These procedures were incorporated into a *Test and Measurement Procedure Manual* which, under a document control system, was distributed to line operations with quality control responsibilities. The use of such standardized procedures for component evaluation ensured that test data was both accurate and reproducible, from developmental trials through final product certification.

3.2.1.2 Test Method Repeatability and Reproducibility (R&R) Assessment

Because many of the components manufactured at M-C Power were flexible, it was found that component placement and fixturing were critical in the measurement process. The difficulty in establishing reference planes for measurement was also an obvious issue on large pieces with complex features. For this reason, a measurement method R&R process was developed to assess the validity of all measurement methods prior to their implementation. Use of this process ensures that test results are valid over varying measurement conditions, and indicates where further test method development may be required. A goal for measurement R&R has been to minimize measurement error to less than the precision of the result reported, such that the error is rounded off. This target has been met for most test methods.

3.2.1.3 Laboratory Operating Manual

An operating manual for QA Laboratory analytical methods was compiled to standardize the procedures used in the analysis of fuel cell components. In the course of the development of many of these methods, it was found that complex samples (such as metallic-ceramic composites) often required special handling to address problems such as sample dissolution and analytical interferences. As these issues were resolved in the course of developmental trials, standardized procedures for each analytical method were documented to ensure that the use of these special techniques was consistent. The use of standard operating procedures in the lab also allowed the training of non-specialized personnel in performing component analyses while maintaining the validity of analytical data.

3.2.1.4 Gas Analytical System Operating Manual

Standard operating procedures were also developed for the operation of the analytical instrumentation system used for stack gas analyses during stack conditioning and testing. Because the results of these analyses were required for the evaluation of stack performance, process control, and stack troubleshooting, there was a need for short turn-around times on a 24 hour a day basis. This required that test operators with no formal analytical training be capable of performing gas analyses as needed. To facilitate this and to ensure the quality of the data generated, an operating manual for the system was developed. This manual addressed routine operation and maintenance and basic troubleshooting procedures. Basic methods have been revalidated prior to the start of each stack test and revised as needed.

3.2.1.5 ISO Quality Assurance Manual

Work began on the documentation of the M-C Power quality program. This program is based upon the specified requirements of the ANSI/ASQC Q9001-1994 Quality System Standard (*Model for Quality Assurance in Design/Development, Production, Installation, and Servicing*), a technical equivalent of the ISO 9001 International Quality Standard. This system provides a general structure for quality programs which, if followed, will lead to formal certification. Numerous procedural drafts were completed for such issues as drawing and control, control of nonconforming materials, and product inspection requirements. ISO certification is planned under Cooperative Agreement DE-FC21-95MC30133.

3.2.2 Quality Control Laboratory

The Quality Control Laboratory was designed and equipped to provide analytical capabilities to support M-C Power's development and manufacturing activities. An initial focus within the laboratory was the development of analytical methods for testing of fuel cell components following stack testing, and methods for interpreting these results relative to pre-test conditions. These results were used to provide direction for developmental activities and to assess the validity of manufacturing specifications. Methods were developed for in-depth quality control analyses which could not be performed in-process, such as photomicroscopy, pore structure analysis, and elemental analysis.

These capabilities generally compliment methods in use by the line operations in ensuring product quality. A summary of analytical methods developed is as follows

3.2.2.1 Porosimetry

A mercury porosimeter (Micromeretics Model 9220) was purchased for the analysis of manufactured components and post-test materials. Porosimetry yields information on pore size distribution and overall component porosity, critical characteristics for pre-test carbonate loading calculations, component matching, and investigations of cell performance issues. Standard operating procedures were created to ensure analytical consistency and accuracy. Porosimetry sampling was instituted as a standard quality control method during production.

3.2.2.2 Atomic Absorption Spectrometer and Sample Preparation

An atomic absorption spectrometer (GBC Model 906) and a microwave sample digestion system (CEM Model MDS2000) were procured, primarily for the analysis of post-test stack components. Sample preparation and analytical methods developed increased sample preparation rates twelve-fold over methods previously used. Analytical methods were developed for fuel cell components, and method development for other in-house applications has continued.

3.2.2.3 Microscopy and Sample Preparation

An optical microscope (Nikon), photographic attachments, sample polisher/grinder, and mounting press were procured for the Analytical Laboratory. Through the use of etching materials and a measurement reticle, visual plate weld inspections and aluminization coating thicknesses could be determined and recorded. Future applications will include analysis of component microstructures and metallographic techniques for assessing plate manufacturing processes.

3.2.2.4 Carbonate Analysis

A wet chemical technique for the analysis of the total carbonate content of post-test cell components was implemented. Used in conjunction with elemental analyses, specific carbonate inventories may be determined and used for validation of component loading and cell performance troubleshooting.

3.2.2.5 Nickel-Coating Test Method

An electrochemical spot test was developed for the qualitative verification of the nickel coating on separator plates. Use of this test has prevented the reversal or omission of nickel-coated materials during off-site manufacturing operations where visual identification is difficult.

3.2.2.6 Total Hydrocarbon Analysis

Two total hydrocarbon analyzers (Rosemount Model 400A) were procured to monitor the binder removal process to indicate the rate of binder elution for use in process control during stack heat-up. This system utilizes a flow-through flame ionization detector to detect the level of organic carbon in a gas stream, used as a relative measure of binder content of the gas. Because of the high boiling pressure of binder constituents, a specialized sampling system was developed to prevent condensation of the binder with the analyzer.

3.2.2.7 Stack Process Gas Analysis

Two dew point sensors (General Eastern Model SIM12H/M1 Pacer) and gas chromatographs (EG&G Model 4160) for monitoring the dew point and gas composition of stack gases were procured and installed, with methods developed for their use. The gas chromatographs utilize a thermal conductivity detector and hydrogen transfer system which allows analyses to be completed in approximately half the time of alternate methods. The automated analytical control and acquisition system was configured and programmed to allow the user to obtain dew point readings, select sample streams, perform chromatographic analyses, and to generate analytical reports from a central computer.

3.2.2.8 Completion of Analytical Test Stand and Operating Manual

Fabrication of an analytical test stand for gas analysis in the acceptance test facility, 20-kW test facility, and bench-scale test facilities was completed. Installation of all gas analytical instrumentation on a mobile rack enabled the use of a single analytical system for multiple facilities.

3.2.3 Quality Control Component Evaluation Test Stand (CETS)

The test stand was originally designed and partial fabrication completed by M-C Power in 1989. The test stand was designed for atmospheric operation of a single, 1000 cm² test cell using a standard fuel mixture of hydrogen and carbon dioxide. The purpose of the stand was to perform component evaluation testing for verification of M-C Power's manufactured active area components. The use of this test stand for this function was limited with the installation of a 20-kW stack testing facility at M-C Power in 1990.

In July 1993 work on upgrading this test stand for operation of small 3 cell 1000 cm² stacks began. The reason for this upgrade work was the modification of the 20-kW stack testing facility to a 1 m² test configuration, and the desire to have the ability to quickly test new stack designs in a small, less expensive test bed. This test stand has been commissioned and is in use at M-C Power.

3.2.3.1 Design Engineering

The objective of the design work in upgrading the test stand for stack operation was integration of cell and clamping device hardware previously used by M-C Power in 1000 cm² stack

testing, and incorporating design concepts learned in the fabrication of the 100 cm² pressurized test stands. This approach is taken in the design of this upgrade to insure successful stand operation, and minimize the cost of the fabrication and assembly. The design of the stand for engineering purposes is divided into four sections. The sections are 1) process gas blending, 2) process gas humidification, 3) unit under test (UUT) fixtures, and 4) effluent gas equipment. In each section the design is kept simple, utilizing readily available, off-the-shelf components whenever practical.

The process gas blending instrumentation provides for blending of the individual bulk supply gases to simulate dry process gas mixtures for introduction to the anode and cathode inlet of the test stack. Gas flow measurement and control are accomplished using the original stand's thermal mass flowmeters. The static mixers included in the design insure complete mixing of the constituent gases of the anode and cathode process gas streams.

The process gas humidification section provides for addition of water vapor to the blended dry gas mixtures from the gas blending section. Temperature-controlled gas saturators are used for both the anode and cathode process gases. Automatic water level detectors and control valves provide for the addition of water to the saturators during operation.

As in the 100 cm² test fixture design, the process gas heating is accomplished by integration of process gas flow paths through the stack's heater blocks that house the electric cartridge heaters. These gas flow paths provide preheating of the process gases to the desired test temperature before introduction to the test stack.

3.2.3.2 Equipment Procurement

Procurement of equipment continued during the design and assembly tasks. As required, stand modifications were identified and the design requirements determined. Most of the fabrication and assembly work, except large machined hardware, was completed by M-C Power personnel in-house.

3.2.4 Pressurized Bench-Scale Test Stands

Pressurized bench-scale test stands were designed, procured, and installed in this subtask to support MCFC technology development and verify improvements in cell and stack technology. The stands are capable of simulating system operating conditions at elevated pressure. These stands are used to generate cell package performance data to assist in projecting the impact of improved cell technology on system performance. Data generated during operation of these stands was used in Subtask 5.1 for developmental testing to resolve engineering issues involving active component specification. Eight test stands incorporating this design have been built to date.

3.2.4.1 Design Engineering

The objective during this effort was to design a test stand that would be simple, cost effective, and flexible tool for verification of improvements in cell performance and technology. The design provides for simulated power plant system operation for verification of improvements in cell material, power density, thermal cyclability, and increased endurance.

The design of the stand for engineering purposes is divided into four sections. The sections are 1) process gas blending, 2) process gas humidification, 3) unit under test (UUT) fixtures, and 4) effluent gas equipment. In each section the design is kept simple utilizing readily available, off-the-shelf components whenever practical.

The process gas blending section of the test stand mixes the individual bulk supply gases to simulate dry process gas mixtures for introduction to the anode and cathode inlet of the test cell. Variable area flowmeters, integrated with differential pressure regulators, provide for gas flow measurement and control. The use of differential pressure regulators is necessary to maintain constant flow during system pressurization and operation. The regulators, by maintaining a constant pressure drop across the flowmeter's control valve, compensate for the changing downstream pressure. Static mixers were included in the design to insure complete mixing of the constituent gases of the anode and cathode process gas streams.

The process gas humidification section provides for addition of water vapor to the blended dry gas mixtures from the gas blending section. Temperature-controlled gas saturators were used for both the anode and cathode process gases. A separate charge vessel provides for addition of water to either saturator during operation. The charge vessel, after being filled with water, is pressurized above the test stand's operating pressure. Manual selection of the system's blocking valves allows filling of the saturators.

The UUT fixture section of the stand includes all the equipment and instrumentation required to maintain and operate the test cell at the required test conditions of temperature, pressure, and current. Several unique approaches were taken in the design of the clamping device and the process gas heating in this section. The clamping device, which applies clamping force on the test cell, uses a standard pneumatic cylinder and four tie-rods protruding through the pressure vessel bottom. Extended seal housings are used to seal the tie-rod as they pass through the vessel. The extended housing design allows the use of standard rubber seals. Process gas heating is accomplished by integration of process gas flow paths through the cell heater blocks housing electric cartridge heaters. The process gas flowpath through the heater blocks preheat the gases to the desired test temperature before introduction to the test cell. All these devices differ from those used in the past for operation of bench scale cells.

The effluent gas equipment section of the test stand contains all the equipment required to control the containment vessel and test cell's operating pressures. In addition, this section includes condensers and collection vessels in the effluent process lines running from the test cell to remove water from the gas streams.

3.2.4.2 Equipment Procurement

Upon completion of the design of each section a bill of materials was developed for the equipment necessary for fabrication. Bidding packages and work scopes for fabrication and assembly of the test stands were developed and issued.

Inspection trips were made every two weeks to the contractor chosen for the fabrication and assembly of the test stands. The purpose of these trips was to answer any fabrication questions the contractor might have had and insure delivery of the stands to M-C Power on schedule. During these meetings, shop fabrication work and drawings were reviewed and approved. Delivery of the first test stand to M-C Power was made on September 30, 1992. This date was six months after beginning the original engineering design work for these stands.

3.2.4.3 Commissioning

To minimize the time required to verify equipment operation under actual test conditions, a test cell was constructed and tested in one of the first four test stands constructed. During operation of this cell various tests were conducted to verify equipment performance. Also operations were conducted to verify the ability to acquire the necessary cell test data that would be required during test operation. The tests included cell operation from 1 to 3 atm of system pressure, cell polarization, fuel utilization, wet seal efficiency, cell resistance (iR), and cell process gas analysis.

During this test several design issues were identified. The first problem encountered occurred when loading the test cell to high current densities. A limiting DC load system current was encountered. Measurement of the test system voltage drops, with the test cell under load, indicated high resistance in the hardware connecting the cell to the vessel's electrical feed-through glands. In addition, the size of the wiring from these glands to the DC load system proved inadequate to meet the minimum resistance requirements necessary to properly load the test cell. Several design changes were required to solve this problem. The first was the doubling of the cross sectional area of the hardware connecting the test cell to the vessel's electrical feed-through glands. The second was increasing the electrical gland electrodes to 0.25" diameter shafts. The third was to add welding cable from the electrical gland directly to the test stand's electronic load device. These design changes have been incorporated into the test stands fabricated.

The second issue identified during this test was the failure of two clamping device tie-rod seals during operation at elevated operating pressure. Temporary external seals were fabricated and installed to continue the commissioning test to 3 atm pressure. After discussions with the seal manufacturer's engineers, it was discovered that they originally recommended a seal that would not meet the design pressure requirements. Several other seal manufacturers and designs were identified and sample seals obtained for evaluation.

To evaluate the multiple seal designs, a test fixture consisting of the extended seal housing, clamping device tie rod, and pressure containment plate was fabricated and assembled. The candidate seal designs were each loaded into the test fixture and pressurized at 10, 20, 30, 50, and

60 psig (413 kPag). While pressurized, the clamping rod had side load applied to simulate test fixture alignment and compare seal performance. The results of these tests indicated that an unloaded cup seal design would not leak at these pressures, including the side loading conditions. The unloaded seal design chosen from this testing is rated to 750 psi (5162 kPa) and offered the best low pressure performance of the designs tested. In addition, this seal design also returned to its original shape after being exposed to hot temperatures. The unloaded cup seals have been incorporated into the design of the test stands.

3.3 Subtask 3.3 Acquire Separator Plate Mapping and Component Cutting Machines

Objective:

To acquire component mapping and cutting machines to measure and trim active area components and separator plates to replace high cost services provided by outside vendors.

3.3.1 Component Mapping Machine

A coordinate measuring machine (CMM) was procured for measurement of stack hardware components and assemblies. This system, a Sheffield Cordax model RS150, consists of three main components: the three-axis CMM, a main processing unit, and a desktop computer. With an intrinsic accuracy of ± 0.007 millimeters (approximately 0.0003 inches), the system can measure all hardware components used at M-C Power to an accuracy almost ten times greater than established tolerances.

3.3.1.1 Clamping Fixture and Procedure Development

It was found early in measurement method development that the greatest problems in part measurement were related to the inherent flexibility of many hardware components. Minor changes in the orientation of parts and the effects of "ripples" or "bows" in the parts could have an extreme effect on the measurement of minute features. In many cases, it was found that repeated measurements of the same part could vary by as much as the width of the allowable tolerance due to flexing of the part. For this reason, development work was performed to identify those factors that contributed to measurement variance and to develop procedures to address these factors. Eventually a part fixturing system was implemented to ensure that measurements performed were repeatable and reproducible to within a given percent of the component tolerance, typically about 20% of the tolerance width.

3.3.1.2 Measurement Program Development

The CMM utilizes a version of BASIC programming language, customized by the manufacturer for programming the system to perform its measurement routines. Reliability of the system was improved by changing the way in which the measurements were referenced. A subroutine was added to cause the system to perform an initial "location" of the part. Once this was complete, the procedure was repeated, using the preliminary part location references as a starting point. The result was that much of the error introduced by the initial placement of the part by the operator was eliminated, improving the reliability of measurement data. Additionally, programs were rewritten to perform multiple measurements of a feature and to average the results to further improve data accuracy.

3.3.1.3 Data Processing and Output

The basic CMM output was a "hard copy" of tabular data. Because of a unique file format, this data could not readily be exported to other programs for statistical or graphical analysis. Initially, the data had to be re-entered into another program to achieve this. Programs were written to import this data into a spreadsheet format such that data conversion, statistical analysis, and graphing of data could be completed within minutes of performing a measurement. This reduced the time required for interpretation and improved the throughput on the CMM.

3.3.1.4 Operator Training and System Preventive Maintenance

Because of the complexity of the CMM system and manufacturing delays caused by downtime, a detailed preventive maintenance program was developed and implemented to improve the reliability and availability of the system. This program stipulated frequencies for maintenance to be performed by system operators and annually by the vendor. Because it was found that operator technique could also play a significant part in the reliability of data, a formal M-C Power cross-training and certification program was developed and implemented for all operators to ensure that users of the system were qualified to perform required measurements.

3.3.2 Matrix Electrolyte Cutting/Trimming

During the course of the Unocal effort, M-C Power acquired and rebuilt a used hydraulic press. With this press and steel-rule dies, M-C Power has been able to cut and trim electrolyte matrix tapes in-house. M-C Power has therefore eliminated use of an outside vendor. By performing this operation in-house, improved control over this operation and quality has been achieved. Repetitive material handling has been eliminated and the incidence of broken parts has been reduced. In all, M-C Power has saved an estimated \$75,000 per stack or \$300/kW by implementing this procedure.

3.4 Subtask 3.4 Fabricate Full-Area and Full-Height Stack Assembly Rig

Objective:

To design and fabricate a rig for the assembly of full-area, full-height stacks. This rig will be installed at M-C Power's facilities and utilized to assemble the full-area stacks to be tested during the program and to assemble the 250-kW stack for the power plant test.

Discussion:

In partnership with an automation company, M-C Power designed and fabricated a Semi-Automated Pick & Place Cell Handling System. This system consists of a pneumatically operated cell gripper capable of picking up an individual cell sub-assembly package and placing it on top of another cell sub-assembly package until the complete 250-cell stack has been assembled.

Integrated with the *Semi-Automated Pick & Place Rig* are robust tooling and fixturing alignment columns that insure that the stack is perpendicularly aligned as it is assembled. The use of this Cell Automation Handling System alleviates repetitive labor and reduces assembly cycle time. This system was in place for the Unocal stack assembly.

In addition to designing a semi-automated cell rig, an automated stack assembly machine has been conceptualized and designed. The automated stack assembly machine will consist of three major components: 1) Element Placement Vehicle, 2) 180 degree Turnover Fixture and 3) 4-Axis Cell Manipulator Assembly Machine.

Fabrication and installation of this new equipment is planned during commercialization.

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4. TASK 4. TESTING FACILITY DEVELOPMENT

The objective of this task is to address issues impeding the development of testing facilities to support MCFC stack research and power plant development.

4.1 Subtask 4.1 Construct Power Plant System Test Facility Designed under Task 2

Objective:

To construct all subsystem modules and erect/complete the 250-kW power plant at a Unocal site located in southern California and to execute shakedown and start-up activities which will culminate in turnover of the power plant to operation and execution of the approved test plan.

Discussion:

4.1.1 Plant Organization

4.1.1.1 General

The fuel cell demonstration plant, which is the result of a cooperative agreement among M-C Power, Unocal, and other sponsors, consists of two main sections. Specifically, these sections are the fuel processor system and the fuel cell system. The plant plot plan shows the relative location of the major pieces of equipment which constitute these two systems.

4.1.1.2 Fuel Processor System

The fuel processor system consists of the fuel-steam reformer furnace, the associated piping and the valve skid. The reformer, together with its associated equipment, was designed and manufactured by KTI, Inc, a major international engineering firm. The specific office that supplied the reformer was located in Rome. The major equipment for this system was skid-mounted to facilitate the installation. By mounting the equipment on skids, smaller sub-systems of the entire plant were pre-tested and then shipped to the job-site.

4.1.1.3 Fuel Cell System

The fuel cell system consists of the anode inlet heater, the enclosed fuel cell stack and the BOP skid. The fuel cell stack was manufactured and tested at M-C Power, where it was also installed in a pressure vessel. The pressure vessel assisted in the transportation of the fuel cell to the job site.

The BOP skid, manufactured by Stewart & Stevenson, included the following components:

- Catalytic combustor
- Hot gas mixer

- Hot gas recycle blower
- Recycle gas cooler (HRSG)
- Cool gas recycle blower
- Turbo-charger
- Cathode start-up heater

Additionally, the skid contains piping, insulation, valves, expansion joints, and on-skid instruments and controls. Stewart & Stevenson prepared a final report to M-C Power on their work effort. The Summary section of that report is included below. The Stewart & Stevenson effort that the summary describes can be subdivided into the three phases of design, procurement, and construction. They are presented together for cohesiveness.

4.1.1.3.1 Design

During the initial phases of the project, Stewart & Stevenson personnel served in an advisory capacity, performing technical reviews of design documents provided by Bechtel and M-C Power. Project status meetings were attended, communication lines were established, and design requirements were definitized.

Concept development activities were initiated based on preliminary technical data provided to Stewart & Stevenson and a few general arrangement concepts were prepared to explore alternatives, estimate overall size, and integrate the concepts with the site plan concurrently under development by Bechtel.

4.1.1.3.2 Procurement

As specification data sheets became available for accessory components (i.e., instruments, valves, etc.), Stewart & Stevenson prepared from Bechtel bid packages and draft purchase descriptions, a list of potential suppliers. Bids were solicited from qualified vendors with emphasis on long lead items.

During the solicitation process, bidders' questions were reviewed and forwarded to Bechtel when specification data sheets required adjustment or viable alternatives were proposed that required Bechtel input.

All bids received for items defined via Bechtel-generated specification data sheets were forwarded to Bechtel for their review and participation in the source selection process. Final source selection was predicated on joint recommendations of Stewart & Stevenson and Bechtel with concurrence from M-C Power.

As the procurement cycle accelerated, major equipment orders were placed by Bechtel via M-C Power. Accessory component orders were placed by Stewart & Stevenson with M-C Power's concurrence and more definitive design information became available for use in the concept development efforts.

As more definitive major equipment and component technical data became available, additional detailed general arrangement concepts were developed and presented for team member comments and recommendations. Based on trade-off between size and accessibility, a general arrangement drawing was developed. This became the master layout from which all detailed fabrication drawings were generated.

With the overall concept defined and the procurement cycle well underway, the next phase of the project work efforts concentrated on vendor certified drawing review, comment and approval. The layout was updated and refined (based on latest definitive vendor drawings), and the initial Stewart & Stevenson detailed skid base and superstructure design.

A preliminary pipe stress analysis was performed to identify potential problem areas anticipated as a result of the relatively high system operating temperatures and the associated pipeline thermal displacements. The results dictated refinement of pipeline routings both inside and outside the Stewart & Stevenson skid and incorporation of flexible expansion joints in a variety of combinations. The results also provided a preliminary insight relative to potential equipment nozzle loads induced by pipeline weights and thermal displacements. Based on these results, pipe runs were further refined to provide more inherent flexibility and space for accommodation of expansion joints.

Since major equipment allowable nozzle load criteria had not been established, a special effort was implemented to minimize pipeline induced nozzle loads to the lowest level possible. Pipe runs were further tailored in conjunction with a second, more comprehensive pipe stress analysis, with the prime goal being to minimize major equipment nozzle loads. The results were forwarded to Bechtel for coordination with major equipment suppliers and confirmation of acceptability. Some of the major equipment items required nozzle reinforcements to accommodate the minimal loads predicted by the pipe stress analysis.

4.1.1.3.3 Construction

With pipe run designs relatively firm and Stewart & Stevenson fabricated item designs well underway, raw material requirements were developed. Bids were solicited for piping materials and purchase orders were placed. Stewart & Stevenson engineering design efforts continued with release to production of detail, subassembly, assembly, and installation drawings. Fabrication began with the base weldment. As major equipment items were received, they were mounted on the base and the balance of the structure, pipe runs, instruments, and accessory components were installed during the manufacturing cycle.

Because interior skid space was at a premium, Stewart & Stevenson initiated a concentrated effort to find an alternate pipeline insulating material that would be thermally equivalent to that specified for the hot pipe surface contact areas, but would require less thickness than those dictated by the project specifications. With the introduction of a variety of relatively large diameter expansion joints, reduced thickness pipeline insulation became a mandatory requirement with the Stewart & Stevenson skid general arrangement and overall size previously adopted. A suitable material was identified and project specifications were revised to reflect this improvement.

Fabrication of the Stewart & Stevenson skid was completed during the month of October, 1994. Component functional tests were conducted and pipeline leak tests were performed prior to insulation. The skid was then finish painted, readied for shipment, and shipped to the Unocal site at Brea, California, on November 7, 1994.

Thereafter, Stewart & Stevenson's work efforts were primarily technical support at the Unocal site during the installation of the Stewart & Stevenson skid and throughout the start-up phase, PAC testing, and system operational testing. Stewart & Stevenson project management continued for a short period thereafter, until termination of activities at the Unocal site were confirmed.

Unocal was responsible for hiring and supervising the construction contractor for connecting the various skids into an operable unit. This interconnecting piping also included some of the control valves.

4.1.1.4 Control Center

A central control center was built at the power plant job site, which consisted of an air conditioned control room, a ventilated electrical room and a conference room. Overall control of the process was accomplished through a Bailey Infi-90 distributed control system (DCS). The operator station for the control system was located in the control room and consisted of two personal computers. Another personal computer connected to a modem was used to transmit data to M-C Power's offices on a daily basis, once plant operation actually started.

4.1.2 Fuel Processor Equipment (Steam Reforming)

4.1.2.1 Natural Gas Pretreatment

Natural gas entering the power plant is preheated and treated for sulphur removal before being sent to the reformer. The desulfurization process is possible with no hydrogen reduction due to the very low sulfur content of the untreated natural gas.

4.1.2.2 Steam Reforming

The reformer reacts natural gas with steam to produce reformat (carbon monoxide and hydrogen) over a nickel-containing reforming catalyst. The reformer furnace is a bottom-fired furnace using untreated natural gas. The reforming reaction occurs in the furnace radiant section with the reactants flowing downwards in four parallel catalyst packed vertical tubes containing sufficient reforming catalyst for five years of operation. Reformer performance conditions have been set at a 1400°F (760°C) maximum effluent outlet temperature using a 3.5 to 1 molar steam to carbon ratio. An overall furnace efficiency close to 74% has been estimated for full load operation.

4.1.3 Fuel Cell Equipment

4.1.3.1 M-C Power IMHEX® Fuel Cell Stack

The M-C Power IMHEX® fuel cell is a molten carbonate fuel cell using state of the art internal manifolding and heat exchanger concepts. The fuel cell stack for the 250-kW plant consists of 250 individual cells. Internal manifolding distributes anode and cathode feed gases to the cells and collects the anode and cathode exhausts from the cells to two common headers. In each individual cell anode and cathode gases flow counter-currently.

The molten carbonate fuel cell operates by transfer of oxygen as carbonate ion from the cathode to the anode through the electrolyte, which is a mixture of lithium and potassium carbonates. To maintain a charge balance, electrons are consumed at the cathode and produced at the anode, setting up a flow of direct current.

The molten carbonate fuel cell performance was estimated using a previously developed performance model which has been verified by IGT and M-C Power test data. At the nominal operating point, the model predicts 0.705 volts/cell.

4.1.3.2 Catalytic Combustor

The purpose of the catalytic combustor is to oxidize the residual hydrogen, carbon monoxide, and methane in the anode effluent. The catalytic combustor consists of the following major components: burner assembly, post burner quench zone, catalytic zone, and post catalytic mixing zone. It is designed to handle both gases that will produce a stable flame when mixed with air and those that require a catalyst for oxidation.

Anode exhaust gases are mixed with air in the burner assembly and, if the anode exhaust gas heating value is great enough, produces a flame. The mixed gases then flow through a catalytic zone to ensure all gases are completely combusted, regardless of the gas heating value. Gases exiting the catalytic zone are mixed with excess cool recycled gas and excess air in the post catalytic mixing zone.

4.1.3.3 Hot Gas Recycle Blower

The hot gas recycle blower is a centrifugal blower with a maximum operating temperature of 1300°F (704°C). Blower seals are specified to be oil free to prevent oil from contaminating the cathode feed and possibly depositing in the fuel cell. The blower speed is varied through a variable speed motor to control the cathode flow. The blower is sized for the maximum cathode flow rate, which occurs at maximum load and 80% anode fuel utilization. At typical operating conditions, the hot gas recycle blower can supply cathode feed in the range of 613 to 3007 scfm (17 to 85 scm/min) at 1050°F (565°C).

4.1.3.4 Recycle Gas Cooling

The cathode inlet temperature control is maintained at 1050°F (565°C) by cooling 1290°F (700°C) cathode exhaust gas down to below 400°F (204°C) for recycle back to the cathode inlet. The cathode exhaust gas is cooled in a kettle-type steam generator to produce 165 psia (1134 kPaa) saturated steam. A constant gas flow is maintained on the tube side of the steam generator via the gas recycle blower and a circulation line.

4.1.3.5 Turbocharger

The purpose of the turbocharger is to deliver 797 scfm (22.5 scm/min) of compressed air to the catalytic combustor and fuel cell by expanding the cathode exhaust. The energy available in the cathode exhaust exceeds the turbocharger requirements. Consequently, a waste gate is provided to bypass the turbocharger and to divert exhaust gas directly to the stack. This waste gate maintains the desired backpressure in the fuel cell system and provides overspeed protection for the turbocharger. The lube oil system for the turbocharger has a pressure less than the operating pressure to prevent the turbocharger seal oil from contaminating the incoming air.

4.1.3.6 Inverter

The inverter regulates the amount of current drawn by matching the impedance of the fuel cell. The fuel cell DC power is first transformed to higher voltage DC power and then inverted into AC power. The inverter has a solid-state design and produces 3-phase, 480 V AC power with less than 3% total harmonic distortion. An overall efficiency of 92% is expected from the inverter.

4.1.4 Major Control Concepts

There are several control concepts that have been designed for various types of operations. During normal operation the plant is designed to respond to increased current demand and to control stack differential pressures. Differential pressures must be controlled to maintain the integrity of the fuel cell wet seals. These wet seals prevent the mixing of anode and cathode gases, as well as isolating these streams from the vessel. There are several controls in place to control the pressure gradients.

Besides normal operation, controls are in place for standby and hot hold I, hot hold II, hot hold III, warm hold, start-up and shutdown. There are specific actions designed to take place whenever one of these operating states is chosen.

4.1.5 Pre-commissioning

4.1.5.1 System Cleanliness

Several activities related to the cleanliness of the system must take place to ensure proper operation of the power plant. All of the piping in the plant was air blown to remove all construction

debris, welding slag, etc. All control valves identified on a list were flushed with all the proper precautions taken depending on the type and material of the valve. The boiler feedwater and recycle gas steam generator were flushed with feedwater. The turbocharger lube oil system was hand cleaned where feasible. The interiors of the desulfurization vessels were hand cleaned to insure that the inside of each vessel was clean, dry and free from loose scale and debris.

4.1.5.2 Mechanical Component Level Testing

Mechanical component level testing was done to ensure that the mechanical equipment was ready for initial operation. This testing consisted of pre-run checks of all non-rotating equipment, automatic valves, and control devices. It also included verifying alignment of all rotating equipment, verifying proper lubrication of all equipment, verifying speed on all rotating equipment, and performing vibration level checks on rotating equipment with drivers above 50 HP.

4.1.5.3 Electrical Component Level Testing

Electrical component level testing was performed to ensure that the electrical equipment was ready for initial operation. This testing consisted of inspecting all power transformers, CTs, PTs, secondary circuits, and electrical systems and equipment. It also included performing megger, polarity, and high voltage insulation resistance testing of power cables and buses, inspecting and cleaning control panels, breaker cubicles, etc., wire and continuity checks. The inspection and testing was used to verify that all lighting panel and control power circuits were numbered and tagged properly, and to set all limit switches.

4.1.5.4 "Controls" Component Level Testing

Controls component level testing was used to ensure that the control equipment was ready for initial operation. This testing consisted of performing a calibration check of all of the facilities instruments and performing instrument loop checks. These were used to verify that all instruments and components comprising the loop functioned as a loop and provided input or output as required or within the correct value and tolerance.

4.2 Subtask 4.2 Upgrading of Existing, U.S. Government-Owned, Test Facilities

Objective:

To upgrade the existing, government-owned 20-kW test facility to improve its reliability for long-term operation.

Discussion:

4.2.1 20-kW Test Facility Modifications

4.2.1.1 Design Basis

The DOE test facility was designed and constructed by Lummus-Crest Division of CE-ABB under DOE Contract DE-AC21-88MC25026. The original design basis was the operation of 10-cell, full-area stacks producing about 10 kW. Therefore, the design was adequate for the operation of Stack MCP-2 which contained 70 subscale cells yielding about 8 kW. However, the facility, as it existed for Stack MCP-2, was not capable of handling the flows required for a 20-kW stack test. The original design had called for an additional process air blower, and additional anode and cathode exhaust blowers to be installed in parallel with the existing blowers to handle the full capacity of a 20-kW stack.

4.2.1.2 Process Modifications

In upgrading the system in preparation for the first 20-kW stack test, Stack Test MCP-3, the following process modifications were required to meet the new flow requirements.

4.2.1.2.1 Water Seal Drums

Two new water seal drums were installed on the anode and cathode feed lines. The new manifold design feeding gas to the fuel cell incorporates orifice plates to properly distribute the feed gas to each of the three branches of the manifold. For proper operation, the manifold requires a higher delivery pressure than the former water seal drums were capable of handling. The former water seal drums provided relief at about 24 to 27 inches w.c., while the new water seal drums will relieve at 40 to 43 inches w.c.

4.2.1.2.2 Process Air

The original design called for three process air blowers, each having a design capacity of 47 CFM of air. Two of these blowers were installed for Stack MCP-2. To meet the flow requirements of Stack MCP-2, both blowers were required to run continuously. It was also determined that these blowers did achieve their design capacity of 47 CFM, each.

To meet the flow requirements of Stack MCP-3, it was determined that installation of the third blower (of 47 CFM capacity) would not meet some of the new flow requirements which were revised in August 1991. Furthermore, all three blowers would have been required to run continuously. Therefore, it was decided to replace the air blowers with two units of larger capacity. The new units were each sized to supply 100% of the process requirements (210 CFM), allowing for 100% stand-by capacity. The new units require the same floor space as the two former blowers, run at a lower speed, and produce less noise.

4.2.1.2.3 Feed Gas Measurement and Control

To accommodate the increased cathode air flows discussed above, the associated flow measurement and control equipment was increased in flow capacity. This modification required larger piping, a larger control valve, and a second rotameter to be installed in parallel with the existing meter.

In addition to the new rotameter for the cathode air, eight other rotameters were purchased to either replace, or to be installed in parallel with, the former meters to measure the higher flows. [Note: the former rotameters were sized exclusively for Stack MCP-2 and installed to provide a back-up capability to the electronic turbine meters which were experiencing reliability problems.]

A new electronic flow meter was also installed on the anode steam feed replacing the former turbine meter. The new meter is a "V-Cone" meter which operates on a differential pressure. The meter is similar to an orifice plate, except that the flow passes around the sides of the cone which is positioned in the center of the pipe. The shape of the cone also modifies the velocity profile of the flow and increases the turndown capability of the meter.

4.2.1.2.4 Exhaust Gas Blowers / Coolers

As mentioned earlier, the original design called for two new exhaust blowers to be installed — one in parallel with each of the existing anode and cathode blowers — to handle the 20 kW capacity. The original design also specified a second cathode cooler to be installed to handle the additional heat load and maintain a lower pressure drop. This approach was not pursued for a number of reasons involving operational performance, flow measurement, and physical space and piping constraints.

The modified design uses larger heat exchangers to cool the gases to a lower temperature and, on the anode side, condense most of the water from the stream. The gas with entrained water flows directly into a gas-liquid separator. The gas exits the separator out the top, while the water drains down into a blow-down drum. The blow-down drum can be temporarily isolated from the process stream allowing it to drain freely.

The larger anode cooler required for this scale-up was obtained by reusing the cathode cooler which was being taken out-of-service, thus reducing equipment cost. A new, larger cathode cooler was purchased. Due to its large size, existing space constraints, and to simplify piping modifications, it was mounted on top of a twelve foot high platform. The platform was built as an extension of existing steel used for pipe supports.

By cooling the gases to a lower temperature, removing the water from the stream, and changing the recycle ratio around the blower, the volumetric flow is reduced such that only one blower is required instead of two.

For Stack MCP-3, no water was added to the cathode feed gases and thus no condensate was formed. The cathode exhaust, therefore, did not have a condensate separator and blow-down drum. It was later decided to feed water to the cathode side for Stack MCP-5 to simulate system gas conditions. Condensate separation equipment and a blow-down drum of similar design, although larger, was later installed for the cathode exhaust.

4.2.1.2.5 Exhaust Recycle Loop Control

The control of the recycle loop around the exhaust blowers was improved by installing a throttling valve in the exhaust line downstream of the recycle loop. Formerly, the pressure upstream of the recycle control valve was determined strictly by the frictional line losses of the gases flowing out the exhaust stack. The operator had no control over this pressure which generally was lower than required to provide sufficient recycle flow. Much of the recycle flow was through the unloading valve (used for start-up) which was difficult to control and could cause excessive heating of the blower. The new valve provided better control of the recycle loop and permitted the blowers to run cooler.

4.2.1.2.6 Exhaust Gas Flow Measurement

New flow meters were installed in the exhaust piping downstream of the exhaust blower and recycle loops. The former flow meters used thermal dispersion technology which is sensitive to, and generally involves proprietary methods to compensate for, variations in gas density, heat capacity, and thermal conductivity. The presence of water vapor in the stream near its dew point can condense and re-evaporate, thus causing the electrical conductance between the probes to vary greatly, resulting in erratic and inaccurate measurements.

The new flow meters are annubars which operate on differential pressure. The new system includes temperature and pressure compensation and a dedicated flow computer.

4.2.2 Binder Removal Development

4.2.2.1 Background and Design Basis

The binder removal process is the phase during the commissioning of a molten carbonate fuel cell when a variety of volatile organic compounds (VOCs) and hydrocarbons are driven off by high temperature. The objective of this task addressed the design aspects of the containment and capture of all noxious, toxic, or otherwise hazardous materials which may be generated by the process. Effort was made to keep process emissions to a minimum and to meet or exceed all applicable federal, state, and local emissions regulations.

During the commissioning of the fuel cell stack, the temperature is slowly raised using a mixture of hot gases, typically nitrogen. As the temperature increases, the VOCs and hydrocarbons each reach their respective boiling points and become vaporized and are carried out of the fuel cell stack by the flow of nitrogen. The resultant effluent is a mixture of various VOCs, hydrocarbons,

and nitrogen whose composition is a function of the initial binder composition, vapor pressures, flow rate of the nitrogen carrier gas, temperature, and time.

The binder removal emissions control system was designed as an auxiliary system which can be isolated from the main process flows through the use of valves and/or spectacle blinds. The main process piping also had valves or spectacle blinds to enable the full flow to be diverted through the binder removal system. The binder removal system was designed to withdraw the gases from the main process piping as close to the fuel cell exhaust ports as is reasonably practical.

4.2.2.2 System Design and Configuration for Stack MCP-2

When initially preparing for testing of Stack MCP-2, little was known regarding the composition of the VOCs emissions or their behavior. It was believed that the primary constituent had a vapor pressure similar to water. Thus, it was felt that a simple cooler could be utilized to condense vapors which would drain down into a collection drum. Thus, the system was built as a single train condensation collection process.

As such, the system was constructed to withdraw the gas exiting the fuel cell from the anode and cathode chambers. These two effluent streams were mixed together and routed via a single pipe through a wall to an adjoining room. The combined gas stream was then passed through two cooling/condensers. The coolers were arranged in parallel to the effluent gas flow (two coolers were needed to provide sufficient surface area for cooling), and in a vertical orientation with the effluent flowing from top to bottom. Condensed liquid would flow downward with the effluent gases into a collection drum directly below the coolers. From the collection drum the effluent gases passed through two blowers which provided flow and pressure control and then through a single carbon absorption bed. The purpose of the carbon absorption bed was to provide final cleaning of the effluent gases and to remove any remaining hydrocarbons to levels not detectable to human smell (a few ppm).

The system performance did not meet expectations. The amount of binder collected in the collection drum was well below predictions. Binder liquids were found in the blowers and the majority of the binder was passed through to the carbon absorption bed. The binder liquids needed a coalescing surface on which to form because cooling alone was not sufficient.

4.2.2.3 Process Modifications for Stack MCP-3

Further research and investigation was conducted prior to redesign of the system for Stack MCP-3. Through discussions with vendors supplying the base materials for the M-C Power binder formulation, it was determined that caustic scrubbing would provide better results.

This system was also built as a single train process. As such, the system withdrew the gas exiting the fuel cell from the anode and cathode chambers and mixed these two effluent streams together. The combined effluents were then routed via a single pipe through a wall to an adjoining room. The combined gas stream was then passed through two cooling/condensers, as before. The

coolers were arranged in parallel to the effluent gas flow (again two coolers were needed to provide sufficient surface area for cooling), and in a vertical orientation with the effluent flowing from top to bottom. The effluent gasses were then bubbled up through a packed bed of caustic solution. Ceramic packing material was included to provide better gas-liquid contact. From the caustic scrubber the effluent gases passed through a paper filter to capture entrained droplets of binder liquids, and then through the blowers and carbon absorption bed, as before.

The general performance of this system was acceptable. The scrubber, filtration and carbon bed were quite good at removing the organic vapors from the effluent gases. The condensation of the binder effluent on the packing material caused plugging and short circuiting gas passage ways. This indicated a need for improved feed distribution, and length-to-diameter design ratios. The performance of the blowers to modulate flow and control the pressure in the fuel cell was acceptable. However, operators and test engineers expressed a desire to be able to control the flow and pressure on the anode side and cathode side independent of one another.

4.2.2.4 Process Modifications for Stack MCP-4

The process modifications for Stack MCP-4 included the addition of a duplicate set of equipment (except for the carbon absorption bed). This dual-train concept permitted separate control or modulation of the flows and pressures on the anode and cathode effluent streams. The two streams were now joined or mixed just prior to entering the single carbon absorption bed. The carbon absorption bed was changed out for a new, clean unit of the same size and capacity.

An operational problem occurred with the binder removal system. At the time, the electrolyte melting was completed and cathode oxidation had not yet begun. The problem manifested itself in that the fuel cell pressure increased to about 20 inches w.c. The operators determined that the carbon bed at the outlet of the binder-removal blowers had plugged. Also the blowers were not drawing in air from the room (at the blower intake). This air intake was the means to modulate flow from the fuel cell stack and thus control pressure.

Upon inspection of the binder removal system, the following problems or causes were identified:

1. Carry-over of small amounts of liquid binder to the carbon bed.
2. A design change in the new carbon bed.
3. Failure to maintain liquid level in the anode caustic drum.
4. High flow rates through the caustic beds.

Items one and two were the primary cause of the problem. Items three and four were contributing or predecessor causes which may have permitted the liquid binder to reach the carbon bed.

Small amounts of liquid binder managed to get through the caustic scrubber, paper filter, and blower and reached the carbon bed. The carbon bed was of a new design. The old design used

screens and about 8 inches (20 cm) of rock in the bottom of the drum to distribute the gas across the carbon filter bed. The new design used a steel pipe with slits cut into it as a sparger. These slits have very small openings. When the liquid binder wetted the activated carbon it formed a gummy mix which plugged the slits in the pipe.

An inspection of the anode caustic drum indicated the presence of large amounts of caustic salt. The top of the burl saddle packing was covered with two to three inches of salt domes and the walls of the drum were covered with one inch of salt. This was caused by not maintaining the proper liquid level in the drum. The level was allowed to drop quite low before it was filled. And the level had dropped very low again at the time of the problem. By letting the caustic salt out in this manner it is no longer available to react with the binder. The salt domes on top of the packing obstruct proper flow through the packed bed. Thus the scrubbing efficiency is very poor. Also, there appeared to be very little binder in the anode caustic drum which usually appears dark yellow or brown.

In addition, the volumetric flow rates through the drums may have been too large, resulting in low scrubbing efficiency. Note, two blowers were used on this test (one for the anode and one for the cathode) when Stack MCP-3 used only one for the combined anode and cathode effluents. An inspection of the cathode caustic drum indicated that the flow was too large for the packing/dip leg configuration. The packing was blown away from the dip leg by the gas. The scrubbing efficiency was thus reduced by not having the proper flow of gases through the packing.

4.2.2.5 Process Modifications for Stack MCP-5

For the testing of the 20-kW Stack MCP-5, the only process modification was that the caustic solution was replaced with water only. The ceramic saddles were still used in the scrubber drum.

4.2.2.6 Process Modifications for Stack MCP-6

For the testing of the 20-kW Stack MCP-6, the water was again used in place of the caustic solution. However, the ceramic saddles were eliminated from the scrubber drum.

4.2.3 Control Systems Development

The control system used on the 20-kW MCFC Test Facility, as developed in this task, is a modified ABB Kent-Taylor MOD30/PC30 distributed control system. This system is used to control the operation of the process equipment required for stack performance and process simulation tests conducted by the test facility. The system is configured to control 31 process loops and associated functions, including safety interlocks. Instrumentation on the test facility is powered by an uninterruptible power supply (UPS) that assures at least five hours of emergency operation of the stack and process instrumentation. This UPS allows continuous monitoring and recording of key test variables during extended emergency operations.

On December 10, 1990, a simulated stack test was conducted as a pre-commissioning check using the anticipated flow and heating requirements for a 70 cell MCFC stack, with each cell of 1000 cm² (155 in²) active area. On this initial run, the facility operated for 240 hours, and successfully achieved the desired operating temperatures and process gas flows. During this period of operation, control loops were checked for proper operation and performance. Several control loops required minor modification to bring them to the desired performance levels. None of the problems encountered during the operation of the facility were significant enough to affect the test simulation effort. During this testing, equipment failures were simulated along with utility power disruptions.

The upgrading of the control system for this test facility was primarily driven by the test requirements of Stacks MCP-2 through MCP-6. The change in the facility from 1000 cm² ($\approx$ 1 ft²) stack testing (Stack MCP-2) to 1 m² (10.8 ft²) stack testing (Stack MCP-3 through MCP-6) required the major changes to the test facility and control subsystem. In addition, each test provided new knowledge and experience in stack operation. Whenever practical, this knowledge and experience have been incorporated into the control system to provide stable and useful stack testing operation in the facility.

4.2.3.1 Control System Improvements

Upgrading the basic architecture of the control system became necessary because of a need for increased system performance and monitoring functions in the operation of the first stack in the test facility (Stack MCP-2). The increased data acquisition requirements, beyond those originally considered during facility design, and the desire for increased automatic report generation, crowded the two supervisory control stations into over-capacity. During this first test, 199 test variables were to be recorded every 15 minutes. In addition, status reports were to be generated automatically by the control system every four hours. These reports were programmed to summarize stack test operation for operating personnel and include all test facility cell voltages, DC load current, temperatures, pressures, gas flows, and stack displacement.

The system has retained this primary system configuration with modifications limited to control database programming, instrument configuration programming, and an additional instrumentation communication network. The additional instrumentation communication network was required for on-line anode process gas flow switching valves used for Stack MCP-5. These controls allowed for switching of the anode inlet flow configuration to twin "V" during test operations.

The modified control system configuration employs two, independent, supervisory, PC-based control stations to provide on-line data analysis and operator control functions. Both stations have independent data handling capabilities. This feature enables data gathering at different frequencies during specialized test operations. A Local Area Network (LAN) is used to allow each station to obtain information available on the network. This feature allows the control system to parallel multiple microprocessors to increase system performance levels. Graphic operator screens on the work stations have been developed to orient users to the hardware layout, typical control functions, and safety interlock logic. Operation screens on the stations display operating parameters of

equipment and test variables in graphic and tabular formats. The Instrument Communication Network (ICN) is a two wire twisted pair serial interface between individual process control instrumentation and the supervisory work stations. Presently, there are four ICN networks configured to permit peer-to-peer and high level system communication. The individual process controllers are used by the system for continuous regulatory control of the process equipment. In addition, these controllers contain all the functional alarm and shut down limits for each control loop.

The Programmable Logic Controller (PLC) is the primary controller of alarm and safety interlock functions. Overrides have been provided for limited modification of this logic during operation of a test. During start-up, these overrides are used until the fuel cell is on-line and steady state operation is implemented. The PLC is programmed to modify the test facility's operation to a safe stand-by mode if triggered by a major alarm status.

Stack data acquisition requirements are serviced by a Hewlett Packard HP3852A data acquisition system integrated into the standard MOD30/PC30 control system. The HP3852A is a microprocessor based instrument used for product development and physical characterization. This subsystem is the primary stack parameter data acquisition element of the control system.

Modifications to reconfigure the control system for the first 1 m^2 (10.8 ft^2) stack test, Stack MCP-3, 20 full-area cells, was primarily rewiring and reconfiguration of the data acquisition subsystem. Field signal input multiplexer cards from the 1000 cm^2 ($\approx 1 \text{ ft}^2$) test, Stack MCP-2, for cell voltage measurements 21 through 70 were replaced with thermocouple input cards. In addition, the data acquisition hardware (HP3852A) was expanded to accept an additional 20 stack thermocouple inputs. Process control instrumentation was installed to support operation of the new, larger, stack enclosure furnace required for 1 m^2 (10.8 ft^2) stack testing. The controls installed provide for three heating zones of control.

The failure of the facility's field flow transmitters during the operation of the first stack test (Stack MCP-2) resulted in the decision to use the back-up variable-area flowmeters for the primary flow measurements for Stack MCP-3. These flowmeters provide manual flow reading and have no interface capabilities with the test facility's control system. Because of this lack of interface, the control database was modified to allow manual manipulation of the flow values input into the control/data acquisition system.

The control database, programmed into the supervisory control stations, was reprogrammed to accept the expanded system requirements. This expansion increased the system to tracking 168 operational variables with a total system capability of 264 operating variables. Additional operator screens were developed incorporating graphically the data from internally placed cell thermocouples.

In preparation for the second 1 m^2 (10.8 ft^2) stack test Stack MCP-4, the control system was again upgraded to provide improved performance, reliability, and flexibility for test operation. The supervisory control stations had additional memory installed and the system's software was changed to an improved version to utilize the memory expansion. The system communication speed between

the supervisory stations and the process controllers doubled with these modifications. The control database of the supervisory control stations were reprogrammed to take advantage of the increased allowable database size by the improved version of the control software. In addition, the remote operator station was programmed with limited control functions and operator screens, and successfully operated from a field location.

The changes made to the control system in preparation for the third 1 m^2 (10.8 ft^2) stack test, Stack MCP-5, was the synchronization of supervisory control stations' time and date. A second ICN communication network was installed, original ICN interface cards upgraded, and control programming added to support on-line flow valve positioning for twin V fuel flow configuration. Modifications to the system for the fourth 1 m^2 (10.8 ft^2) stack test, Stack MCP-6, was limited to minor control data programming.

4.2.3.2 Field Instrumentation

Because of the poor performance of the flow measurement instrumentation during the December 10, 1990 facility pre-commissioning check, variable-area flowmeters were installed in each gas mixing line as an on-line back-up flow measurement system. During the first stack test, Stack MCP-2, complete failure of all the flow instrumentation was experienced. The back-up variable-area flowmeters were used to complete the stack test. These meters were resized in the facility modification to 1 m^2 (10.8 ft^2) stacks and are still used as the primary flow measurement instrumentation.

Field installation of many new electrical and instrumentation distribution boxes to support the new process equipment, and expansion of the data acquisition subsystem was required for the change to 1 m^2 (10.8 ft^2) stack testing. Instrumentation was removed and reinstalled as necessary to allow installation of the 1 m^2 (10.8 ft^2) stack gas piping system.

An orifice flowmeter was installed in the cathode steam-mixing line for Stack MCP-5 to allow wet cathode system gas to be evaluated. A manual temporary second bellow control loop was installed for evaluation of dual bellows control to reduce stack tilting during operation. Automatic control, and installation of a pressure transmitter and control valve for this second bellow pressure control loop was completed for Stack MCP-6.

4.2.3.3 DC Load Device

The test facility's DC load device controls the direct electrical current produced by the fuel cell stack and dissipates the electrical power produced. The design developed was an expandable system based upon the Hewlett Packard 6050A electronic load mainframes. Each of these load mainframes can accept up to three high power (500 watt) HP50504A load modules. With the test facility configured for 1000 cm^2 ($\approx 1 \text{ ft}^2$) stack testing the load device consisted of six load mainframes and eighteen load modules electrically connected in parallel. This load configuration provided 9 kW DC load capacity and was used to test Stack MCP-2.

The load device is controlled by a Hewlett Packard PC-308 instrument controller, and triggered during transient current testing by a Hewlett Packard HP8116A pulse generator. The control program for the load, written in BASIC and used by the instrument controller, provides control of current setpoints, frequency, and duty cycle. The pulse generator provides a precise trigger to synchronize the switching of the multiple electronic load modules when required during transient current testing.

In preparation for 1 m² (10.8 ft²) Stack MCP-3, the load device was upgraded to a DC load capacity of 21 kW DC with a maximum current rating of 2500 A. This upgrade consisted of the integration of eight new load mainframes. This 21-kW DC load system has been used in all the stack testing in the facility to date.

In July 1991, preliminary engineering was conducted on the design of a bulk DC load bank for testing large MCFC stacks. An engineering work scope was developed and a budgetary cost obtained for design of the high current/low voltage resistance load bank. This device was to be designed with non-electronic power dissipation devices and used for full-area MCFC testing.

4.2.4 Upgrading to 50 kW and Pressurization of 1 m² (10.8 ft²), 20-kW Capacity Stack Test Facility at M-C Power

The initial proposal in response to the PRDA included this task to improve the test system operation by pressurization. The initial design effort had indicated that pressurization of the Unocal power plant system would be required for reasonable operation of the recycle blower. [For that matter, the initial design basis, at Lummus-Crest, of the test facility was a pressurized operation, but this feature was dropped as a cost-containment option.]

One of the early decisions in this task was the construction of a new, second test station, rather than the modification of the original unit. The testing time lost during modification would have seriously impacted the overall schedule of the program.

The 50-kW, pressurized test station was examined, first by an in-house consultant and then by outside engineering companies. The unit was to include a small, natural gas reformer and a control system similar to the Unocal design.

Due to budgetary constraints, the facility was not constructed. If it had been built and operated for Stack MCP-6, as planned, the team would have gained valuable insight into several facets of MCFC stack operation that, by default, were first experienced at Unocal. Among these operating conditions were 1) pressurized operation, 2) integration with a reformer, and 3) operation with automatic control. Had this experience been available, the Unocal start-up would have been much easier and, perhaps, more successful.

4.3 Subtask 4.3 Construct Acceptance Test Facility (ATF)

Objective:

To design, procure, construct, install, and commission a commercial stack acceptance test facility (ATF).

Discussion:

4.3.1 Process Description

The ATF is designed to pre-condition a 50-kW or a 250-kW molten carbonate IMHEX[®] fuel cell stack. Pre-conditioning of a stack prior to shipment eliminates the support equipment necessary to perform binder removal, carbonate melting, and cathode oxidation at the test site. Due to the transient nature of pre-conditioning a MCFC stack, the ATF is a fully manned facility. The end of pre-conditioning occurs when baseline performance standards are established by operating the stack under the following conditions:

Load (Amps)	425 A
Current Density	40 mA/cm ²
Fuel Utilization	50%
Oxidant CO ₂ Utilization	30%

The actual gas composition is dependent on the amount of gas recirculated in the system. The minimum recirculation is 90% for either flow configuration. Recirculation percentages for the anode and cathode gas trains are set and controlled independently.

4.3.2 Process Equipment Design Engineering

The process equipment design work was performed by Xytel Corporation with the following major steps completed for the process equipment skid design:

- ▶ Development of P&ID drawings based on direction from M-C Power.
- ▶ Generation of equipment specifications following the parameters established by the P&ID drawings. Several iterations of specification review were performed to select the equipment based on M-C Power's prior experience with conditioning molten carbonate fuel cell stacks in the 20-kW test facility.
- ▶ Equipment layout and piping arrangements were generated to accommodate the space restraints imposed by the location of the ATF.

- ▶ Development of instrumentation and control strategies based on M-C Power's prior experience with conditioning molten carbonate fuel cell stacks in the 20- kW test facility.
- ▶ Development of electrical drawings and loop diagrams to meet industry standards and the ATF area's electrical classification of Class 1, Division 2, Groups C & D.

4.3.3 Balance of Plant (BOP) Design Engineering

The balance of plant design engineering effort was performed by Raytheon Engineers & Constructors. Meetings were held with the Assistant Village Building Commissioner to review the scope of the work and to assure the village that all pertinent codes were being adhered to in the design of the ATF. Major items completed were:

- ▶ A Code Compliance Review of the Village of Burr Ridge Building Codes.
- ▶ Review of the Village of Burr Ridge Zoning Ordinances
- ▶ Completion of a Code Compliance Check Form

Upon the completion of the code reviews, the balance of plant engineering effort comprised of the following activities was performed:

- ▶ The available electrical power was determined and compared to the existing requirements and anticipated requirements to support the operation of the ATF. This determined the modifications to the building's main switchgear and the development of the electrical drawings and loop diagrams to meet industry standards and the ATF area's electrical classification of Class 1, Division 2, Groups C & D. Also, a motor control center to support the motors, heaters, and ancillary equipment in the ATF was specified.
- ▶ The design parameters for a recirculated water system were determined and a system was developed to support the operation of the ATF, the existing 20- kW test facility and a future 50-kW test facility. The major parameter of the system was to allow the operation of the ATF with one of the other two facilities without the need to use potable water for process cooling.
- ▶ A HVAC system was designed to accommodate the cooling requirements for the process equipment during summer operation and heating requirements during winter operation. In addition, the area classification and operator safety played a significant role in specifying equipment and air duct routing to meet the requirements and yet keep the cost of the equipment down to an acceptable level.

A second HVAC unit was specified to support the computer equipment in the telephone room adjacent to the ATF which previously had its air conditioning unit located in the truck dock. This stand-alone unit and its location were dictated by code requirements.

- ▶ Civil and structural modifications to the building(s) to support the installation of the ATF and its ancillary equipment were performed. Major modifications were made to the existing dry room where the 250-kW molten carbonate fuel cell stack was assembled and in the ATF where a platform was designed to "cover" the recessed truck dock to support the process equipment skids and the fuel cell stack module with its furnace enclosure. A special adjustable dock was designed to transport the fuel cell stack out of the building to the pressure vessel base waiting on a double drop low boy trailer.

Electrical upgrades were made to support the installation of instrumentation and ancillary equipment in the enclosure vessel/fuel cell stack assembly prior to shipment to California.

- ▶ The following utility gas piping systems were designed to support the operation of the ATF:
 - Gas lines for N₂, H₂, and CO₂ were routed via the roof from the bulk gas storage facilities in the rear of the building to the ATF located in the front corner of the building to minimize the impact on manufacturing operations in progress.
 - Water recirculation system supply and return lines were laid out to support the ATF, the existing 20-kW test facility, and a future 50-kW test facility.
 - An instrument air line to operate the control valves and supply purge cabinet gas was orientated to support the ATF equipment requirements.
- ▶ A gas detection/safety system comprised of CO gas sensors, flammable gas sensors, UV detectors and low O₂ detectors was specified for operator and equipment safety. This new equipment was specified to tie into the existing system that supports the 20-kW test facility and resides in the control room.
- ▶ A load device to measure and dissipate the electrical power generated by the 250-kW fuel cell stack during the generation of the baseline performance standards was specified based on past experience with the 20-kW Test Facility.
- ▶ The existing fire protection equipment was modified to accommodate the installation of the process equipment skids and the ancillary equipment in the ATF.

Construction bid packages were developed based on the above specifications and the order in which the work could logically be accomplished. These packages are outlined in Section 4.3.5.

4.3.4 Procurement and Fabrication of the Process Equipment Skids

The procurement and fabrication of the ATF process equipment skids were completed by Xytel Corporation based on the design engineering performed in Section 4.3.2. As equipment was received at Xytel's manufacturing facility in Mount Prospect, Illinois, M-C Power personnel inspected and verified that the equipment met the design specifications. During fabrication of the equipment skids and the installation of equipment, M-C Power personnel monitored the work facility and accomplishments with the schedule. The process equipment skids delivered to M-C Power were pre-piped and pre-wired to accelerate installation. Prior to shipment, the equipment skids were leak tested to insure the system's integrity.

4.3.5 Procurement and Installation of the Balance of Plant Equipment

Construction bid packages were developed based on the specifications generated in Section 4.3.3. After reviewing the bid packages and reconciling any differences between the Contractor's estimate and an estimate performed by a member of M-C Power's project team, the packages became the following construction tasks:

- ▶ Task 1: ATF Floor Framing Fabrication & Installation
- ▶ Task 2: Construction Job Site Preparation
- ▶ Task 3: Stack Assembly Area Fabrication & Installation
- ▶ Task 4: ATF HVAC Fabrication & Installation
- ▶ Task 5: Recirculating Water System Installation
- ▶ Task 6: Conduit & Misc. Electrical Work
- ▶ Task 7: ATF Stack Table Foundation & Structural Steel
- ▶ Task 8: Misc. Electrical Work (MCC to Equipment Skids)
- ▶ Task 9: ATF Process Piping
- ▶ Task 10: Dock #1 Fabrication & Installation

In addition, the following major miscellaneous construction activities were performed:

- ▶ Coating of the dry room floor and the warehouse floor leading into the ATF to support the requirements of the air cart used to transport the 250-kW fuel cell stack within the M-C Power factory.
- ▶ Installation of a removable wall that was necessary to transport the 250-kW fuel cell stack into the ATF, install the furnace enclosure, and then seal the room to meet the area classification of Class 1, Division 2, Group C & D.
- ▶ Installation of utilities and tubing to support the analytical equipment necessary during operation to monitor the fuel cell stack.

4.3.6 Custom Design Efforts

4.3.6.1 Clamping Fixture

The concept used to design the clamping fixture was to use a "puller" mechanism below the test table to pull the top clamp plate down level during pre-conditioning. A second fine adjustment was obtained by utilizing the bellows integral to the fuel cell stack to take up any stack tilting while maintaining uniform clamping pressure on the fuel cell stack.

4.3.6.2 Plenum Insulation Block

The design of the plenum insulation block was necessary to take up any deflection in the test table structural steel due to the weight of the fuel cell stack and ancillary equipment at ambient temperature and at operating temperature. This was accomplished by specifying a castable refractory material and fabricating a structural steel support frame to house the castable material. The castable material's compressibility characteristics and the strength of the structural steel frame accommodated the deflection of the test table under load at operating temperature.

4.3.6.3 Acceptance Test Facility Furnace Enclosure (ATFFE)

The ATFFE was designed with future control expansion as a consideration. The eight control zones can be reworked and grouped, if necessary, to form 20 individual heating zones for improved control during stack pre-conditioning. The size of the 250-kW fuel cell stack required the ATFFE to be built in five sections to facilitate installation and removal of the ATFFE.

4.3.6.4 Stack Sub-Assembly and Assembly Lifting Equipment

Due to the height of a 250-kW fuel cell stack on the air cart used for transporting the stack internally at M-C Power, custom lifting frames were designed and fabricated.

Frame No. 1 was designed to lift only the cathode end plate level for placement onto the fuel cell stack during assembly in the dry room.

Frame No. 2 was designed to lift individually the load plate and the top clamp plate during assembly of the fuel cell stack in the dry room. In addition, this lifting frame, using two lifting points, was designed to lift the entire fuel cell stack module weighing approximately 45,000 pounds (20,454 kg).

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5. TASK 5. STACK RESEARCH

The objective of this task is to identify and resolve issues in engineering, manufacturing, assembling, cost, performance, and endurance involving the stack repeat and non-repeat components.

5.1 Subtask 5.1 Engineering Issues

Objective:

To continuously review the full-area, full-height IMHEX® design and incorporate all improvements/modifications developed during the course of the program.

Discussion:

5.1.1 Active Component Scale-up

5.1.1.1 Anode

The general anode specification remained virtually unchanged throughout the scale-up from 1000 cm² ($\approx 1\text{ft}^2$) components for Stacks MCP-1 and MCP-2, into the continuous casting development for 20-kW commercial-area (1m² or 10.8 ft²) Stacks MCP-3 through the Unocal 250 cell stack.

Only minor tape casting slip modifications were made during the scale-up from 457 mm (18 in) wide tapes to 1295 mm (51 in) wide tapes, which occurred during the manufacture of 20-kW Stacks MCP-3 and MCP-4. Cracking and poor release were eliminated by evaluating and modifying the flowrate and temperature distribution processing parameters within the tape caster.

Major developments were required in the sintering of the full-area tapes to prevent cracking and warping of the sintered components. Coating formulations were developed which lowered the coefficient of friction of the part on the sintering carrier to such a degree that tape cracking did not occur, but allowed some resistance to prevent warpage. In addition, the thermal cycle was developed such that the percentage of chromium metal alloyed into nickel was maximized.

Equipment specifically designed for weighing and measuring the electrodes was also developed: the component weighing machine, the thickness mapping machine, and the strip measuring system for width-thickness distribution of unsintered parts were all designed to handle the full-area, 1m² (10.8 ft²), parts.

Further development was required when continuous casting and sintering techniques were developed for the anode. Continuous casting in this case was defined as simultaneously pouring slurry while also removing components at the other end of the tape caster. Previous to the Unocal production runs, the run lengths were short enough that continuous casting was not required. As a

result of the continuous processing experiments, physical and visual defects appeared which had previously been unknown:

- ▶ Metallurgical inclusions which were later identified as a residue from the tape casting formulation. The inclusions were eliminated by changing the tape casting formulation.
- ▶ Bottom-side defects, resulting from the tape sticking to the carrier belt. Development using alternative release agents and proper drying cycles eliminated these defects.
- ▶ Holes, due to improper degassing. Blade speeds and degassing procedures were modified to eliminate these defects.
- ▶ Cracks, caused by the electrode edge sticking to the carrier belt. These were eliminated by ensuring sufficient drying through belt speed modifications and improved release agents.
- ▶ Discoloration, due to incomplete binder burnout. Modifications in the preheat section of the furnace eliminated these defects.

5.1.1.2 Cathode

The general cathode specification remained virtually unchanged throughout the scale-up from 1000 cm² ($\approx 1\text{ft}^2$) components for Stacks MCP-1 and MCP-2, into the continuous casting development for Stacks MCP-3 through the Unocal 250-cell stack.

The tape casting and sintering scale-up development work was essentially identical to that outlined under Section 5.1.1.1 for the Anode.

5.1.1.3 Electrolyte Matrix Specification

The composition and tape casting procedures for the electrolyte matrices in Stack MCP-6 were changed significantly from the previous stacks, MCP-3, MCP-4, and MCP-5. Seven different solvent systems were evaluated during the scale-up to continuous casting. Major issues that were solved include: cracking during drying, solids settling from the slurry in the doctor blade reservoir, pinholes or air inclusions, and poor release of the tapes. The technical progression across the four full area, 20-cell stacks is summarized below:

- ▶ Stack MCP-3 utilized unrolled outer electrolyte matrix layers to improve the sealing capability of the stack. The inner matrix layer of each cell was rolled to improve its carbonate retention characteristics.

- ▶ Stack MCP-4 utilized fully rolled electrolyte matrices with a tight porosity range to improve the electrolyte management. Leakage across the wet seal was apparent as fires across the wet seals in this stack.
- ▶ Stack MCP-5 employed two different cell types: half-rolled and unrolled matrices for improved sealing capability, and fully rolled inner matrices for improved carbonate retention by the matrix.

Between Stack MCP-5 and MCP-6, a development effort was initiated to eliminate the roll-compaction procedure by casting to the specified porosity. Roll compaction is a very time-consuming and expensive procedure. Also, during production for Stack MCP-5, it was determined that the roll compaction rollers induced porosity variations across the width of the part. Cracking during rolling was common and the fully rolled parts were more brittle than unrolled matrices of the same porosity.

Two different solvent systems were evaluated with numerous dispersants. An alcohol-based tape casting formulation was selected for scale-up trials, based on the higher cast densities that were obtained in 26.5 liter (7 gallon) cast sizes. In addition, the porosimetry of the MCP-6 unrolled electrolyte matrices had a higher percentage of pores less than 1 micron than MCP-5 rolled matrices with the same final porosity.

Modifications were made to the continuous casting process during the MCP-6 matrix manufacturing run: improved temperature control of the take-off portion of the caster improved the release characteristic; a "split-T" slip delivery system minimized matrix cracking, due to solvent lines, and improved the thickness distribution across the width of the tape. These formulations were successfully scaled up further during the Unocal casting run, to the 189 liter (50 gallon) level.

A carbonate loading spreadsheet program was developed to ensure a proper weight basis, grams of carbonate per area of tape. Active component fill requirements and cell hardware and component lithiation reactions are included in the carbonate loading requirement calculations.

Matching procedures were developed for the 250-kW stack such that the carbonate loading required was provided within 5% of the calculated value.

5.1.2 Design, Engineering and Manufacture of the IMHEX® Separator Plate

The production of the flat components, discussed above, required scale-up of existing techniques by a factor of 10, from about 0.1 m² ($\approx$ 1 ft²) to about 1.0 m² ($\approx$ 10 ft²) active area. That effort was initially undertaken for Stack MCP-3. However, the full-area separator plate was an entirely new design, only superficially based on the sub-scale separator plates employed in the 0.1 m² (1 ft²) stacks. A major effort was required for this new design.

In summary, new dies were required for pressing; a 30,000 metric ton (33,000 tons) press was employed for forming; new fixtures were needed for cutting and welding; and new aluminizing

procedures were developed. Each of the steps was an iterative process, with trials, evaluation, revision, and re-trials. For example, even the apparently straight-forward measurement of the plates on the coordinate measuring machine required several iterations of the clamping fixture, with the resulting data improving in reliability through Stack MCP-6.

5.1.2.1 Development of the IMHEX® Full-Area Separator Plate Design

5.1.2.1.1 Introduction

This section documents the design process used in the development of the first-issue, full-area separator plates, as well as the MOD 2 design employed in most of the stack tests and the MOD 3a design used in the Unocal 250 cell stack. This first issue covered in the design process is a definition of the separator plate functional requirements in the MCFC stack.

Figure 5.1-1 is a schematic representation of a single cell in a fuel cell stack, the separator plates on either side of that cell, and the electrodes of the adjacent cells. The separator plates are indicated by the wavy lines. The electrochemistry of the fuel cell occurs in the anodes, cathodes, and electrolyte; the separators are of little importance in the basic electrochemical operation of the fuel cell.

It is common to think of a separator plate as the central element, with the flat active components on either side. Rather, the flat components are the primary elements in the fuel cell, and the separator plates are merely what their name implies — plates that separate individual cells in the stack.

In addition to this minimal electrochemical cell function of the separator plates, they must also provide the following mechanical functions in the internal manifolded MCFC stack:

- ▶ The separator plate separates the fuel gas at an anode from the oxidant gas at the adjacent cathode.
- ▶ The separator plate collects electrons from an anode and conducts them into an adjacent cathode.
- ▶ The separator plate provides the means for simultaneously feeding and uniformly distributing fuel gas at an anode and performing the same functions at the adjacent cathode.
- ▶ Because of steps in the seal rails, the separator plate provides the mechanism for alignment of the other metallic parts of the cell
- ▶ The separator plate provides the means for sealing the edges of the anode chamber and the adjacent cathode chamber.

Figure 5.1-1. Schematic Sketch of MCFC Construction

- ▶ Through perforations in the separator plate, it provides the formation of the internal manifolds and the sealing of these manifolds.
- ▶ The separator plate is the primary mechanical member of the stack and is instrumental in maintaining the structural integrity of the stack

The separator, therefore, is the primary hydraulic element in the cell. It provides for the controlled transfer of gases from the entrance manifolds to the active area, uniform distribution of these gases across the active area, and transfer from the active area to the exit manifolds. It must have mechanical strength to sustain the loads that are imposed upon the stack and, in conjunction with the electrolyte matrix, provides for the gasketing or sealing of the individual reactant chambers. Although these separator plates are of minimal importance in the electrochemical operation of the cell, they are of primary importance in other key aspects.

5.1.2.1.2 Design Basis

The primary design basis for the full-area separator plate designed at M-C Power is the subscale, $\approx 1000 \text{ cm}^2$ ($\approx 1 \text{ ft}^2$) separator plates designed and operated in short MCFC stacks by IGT. This stack design has been titled IMHEX[®], an acronym for *Internally Manifolded Heat EXchanger*. The basic mechanical configuration behind the IGT design is the plate-type heat exchanger, employing this general internal manifolding concept. These heat exchangers have been in commercial use for many years. The IMHEX[®] design builds on that heat exchanger technology.

Figure 5.1-2 is a descriptive sketch, generally characteristic of the IMHEX[®] design. The solid black portions of the separator plate may be considered as the wet seals, or gasketed areas. The manifolds exist in the four corners of the cell. The fuel gas is gasketed from the cathode side of the cell, but feed rails permit flow of oxidant gas from the cathode inlet manifold, across the face of the cell, to the cathode outlet manifold. Similarly, on the anode side of the cell, the cathode gas manifolds are gasketed in isolation, but the fuel can flow across the face of the anode.

A typical, 1 ft^2 ($\approx 1000 \text{ cm}^2$) separator plate is made of three primary components: a main plate that contains the hydraulic characteristics of the cell, and two rail plates that include the main rail around the cell and the blocking rail (opposite a feed rail on the other side of the plate). Similarly, four "feed rails" are included in the total welded unit. Two of these "feed rails" are really exit rails. Each side of the plate has two of these rails, one for feed and the other for exit of the gas flowing over the face of the cell. The feed rails are formed with slots, so that the sealing surface of the rail is the same as the other rails, but the gas can flow between the rail surface and the main separator surface.

The main area of the plate is an embossment of ribs. The main plate is formed from 0.5 mm (20 mil) stainless steel stock.

IMHEX™ Bipolar Separator Plates

Figure 5.1-2. Descriptive Sketch of IMHEX® Design

At either end of the main flow field is a triangular zone called the distribution field. This field was designed to manage gases in crossing flow patterns, one above and below the main plates; this also provides high pressure drop for the flowing gases, to ensure more uniform gas distribution across the face of the cell.

The flow of gas from slots in the feed rail is directed toward an up-protuberance in the distribution field. The gases must flow around the protuberances until they reach the main ribbed area. The gases then flow down the ribs until they reach the exit field. Again, a high pressure drop element is included in the field before the gases exit through the final sealing rail of the cell.

The hydraulic characteristics of the 1000 cm^2 ($\approx 1 \text{ ft}^2$) cell were extensively examined, both mathematically and with cold-flow testing. The hydraulic characteristics of the cell, as estimated by cold-flow testing with gases containing small amounts of hydrogen sulfide, employing lead acetate paper on the face of the cell, showed excellent gas distribution across the face of the cell.

The calculated hydraulic analysis was based on the design basis of 3.4 kPa (0.5 psi or 14" inches w.c.) pressure drop across the face of the cell under atmospheric pressure conditions.

Figure 5.1-3 presents the hydraulic data for the cold-flow test across the 1000 cm^2 (1 ft^2) separator plate. Note that most of the pressure drop was in the distribution fields, as designed, with a lesser amount in the feed rails and minimal pressure drop in the corrugated field. In the cold-flow test, the overall pressure drop varied with the 1.60 power of the gas flow. The primary discrepancy between the calculated pressure drops and those observed on the cold-flow testing was in the distribution field. The Reynold's Number in this zone is in the transition region and the pressure drop was significantly higher than calculated.

In their initial conceptual design, IGT had projected a design for a full-area separator plate that was similar to the 1000 cm^2 (1 ft^2) plate, but three times larger in each dimension, for a total active area of $\approx 9000 \text{ cm}^2$ (9 ft^2). IGT had calculated that this separator plate design would have satisfactory pressure drop when operating at 3 atm system pressure. This design, however, would result in excessive pressure drop when certain additional factors were included:

- ▶ The cathode gas flow for the initial Combustion Engineering, design base-case was about 67% greater than IGT had used for its calculations.
- ▶ As a cost containment element, the test station at M-C Power was designed to operate at atmospheric pressure, rather than elevated pressure. This effect increases the pressure drop several fold.

The net effect of these two parameters is an estimated 69 kPa (10 psi) pressure drop across the face of the cell if the IGT concept for the $\approx 9000 \text{ cm}^2$ (9 ft^2) cell was to be operated at atmospheric pressure and the CE flow rates. Consequently, the hydraulics of the plate were redesigned to minimize the pressure drop on the cathode side of the plate.

**One Sq. Ft. Hydraulic Data
Cold Flow Tests**

Figure 5.1-3. Cold-Flow Hydraulic Data for Sub-scale Separator Plate

5.1.2.1.3 Full-Area Separator Plate Hydraulic Design

The first element controlling the design of the separator plate is the maximum width of the electrodes. The tape casting equipment that was owned by M-C Power was the largest in the world, at that time. Electrodes that had been cast with this equipment, after shrinkage during sintering and trimming, had a maximum width of 813 cm (32in). This criterion, therefore, was one of the primary concerns in the plate design.

The total active area was selected as a nominal 1 m^2 (10.8 ft^2). At this size, the then-estimated maximum shippable 400-cell stack would deliver about 500 kW and the aspect ratio, height to area of base, would be reasonable.

The first decision was to employ multiple inlets and outlets, permitting the gases to flow in the short direction of the cell. With this approach, the flow path for the gas is much shorter and the amount of flow in any rib is also reduced. Both of these factors reduce the pressure drop of the plate.

The next decision was to increase the rib spacing. M-C Power increased the rib spacing by about 28%, at the suggestion of the plate fabricator, to achieve better plate flatness. A flat area was added to the top of each rib for better electrical contact.

The included angle of the distribution field in the IGT design was increased for the full-area plate. Adjustment of this angle increased the relative effective area of the cell.

The configuration of the distribution field was given significant attention. The original field configuration of the subscale separator plate was unsatisfactory, both from the difficulty of fabrication and the high pressure drop that would result in the larger cell. Several different configurations were considered. The "interrupted rib" was selected as preferred. This interrupted rib field consists of a series of grooves, similar to the ribs in the main flow field, on the cathode side of the plate. Each groove in the cathode side of the distribution field is fed by one slot in the feed rail between the active area and the cathode inlet manifold. On the anode side of the plate, a series of openings are created that permit the gas flow across the anode face of the cell. Thus, the cathode side of the cell has large grooves, that are periodically interrupted, to carry the relatively high cathode gas flow rate. On the anode side, however, small orifices are created for channeling the lower flow rate gas.

On the cathode side of the distribution field, one groove in the distributor field precisely feeds two grooves in the main field. The intersection of the two fields is so configured that the flow distribution is equal. Therefore, the flow in each groove of the distribution field is twice as high as the flow rate in a groove in the main field. Further, because of the interruptions in the grooves, the effective area of the groove is not as great. Nevertheless, the velocity of the cathode gas in the distribution field is still laminar. There is no gas-liquid film phase separation at the expansions and contractions and the pressure drop across the distribution field is relatively low.

Just as the cathode side of the cell has half the number of grooves in the distribution field as in the main field, the anode side had half as many rows of "orifices" to carry the anode gas to the main area. Similarly, each of these rows of orifices has its own corresponding slot in the anode feed rail.

5.1.2.1.4 Other Considerations

The initial design of the full-area separator plate was primarily concerned with improvement of the hydraulics. Consideration was given to redesign of the wet seal rails, primarily to determine if a softer rail could be developed. However, the modification of the hydraulic design, by itself, was considered to be a sufficient deviation from the proved design of the 1000 cm² (1 ft²) component. Therefore, the seal rail, blocker rails, and feed rails were generally similar to the design of the 1000 cm² (1 ft²) components. These components generally became softer because of minor modifications to the plate dies, to improve flatness, and are significantly softer in the next generation MOD 4 design.

5.1.2.1.5 Hydraulic Testing

Combustion Engineering undertook the cold-flow modelling of a machined section of one quadrant of the full-area separator plate. Projections for the pressure drop in the cell, together with the data for Stack MCP-3 are presented in Figure 5.1-4. The data indicated that the pressure drop was about equal in each of the five flow areas: the feed rail, the inlet distribution field, the main corrugated field, the exit distribution field, and the exit rail.

Stack MCP-4 had similar pressure drop characteristics. These data indicated that, although the improvement in hydraulic characteristics of the plate is significant and permits the testing of the cells at atmospheric pressure conditions, the pressure drop across the cell is still sufficiently large at design conditions that the parasitic power of a recycle blower would be prohibitive in a system operating at atmospheric pressure. Rather, elevated pressure operation is required for reduction of the velocities, lower pressure drops, and satisfactorily low parasitic power demands.

Stack MCP-6 had a much higher pressure drop for the cathode flow. A change in constructional techniques had been made to improve the stack integrity during start-up. This change, however, resulted in crushing of the feed rails. A redesign of the feed rail system discussed later, was made to improve the feed structure on the plate, MOD 3a, and also reduce the pressure drop.

5.1.2.1.6 Manifolds

Combustion Engineering's calculated hydraulic analysis indicated that the manifolds in the MOD 1 design of the full-area separator plate were too small to permit reasonable cell-to-cell gas distribution for tall stacks. Consequently, the manifolds were enlarged for the MOD 2 design. This configuration is approximately the largest manifold area obtainable, given the maximum available plate raw material width of 1100 mm (43 in).

Figure 5.1-4. Pressure Drop Across Cathode Side of Full-Area Plate

The discussion above outlines the decisions which were made in the hydraulic design of the first issue, MOD 2 and MOD 3a full-area separator plates.

5.1.2.2 General Separator Plate Mechanical Design

The separator plate is constructed of three primary pieces: the corrugated plate and two main rail plates, and ten feed rails except in the MOD 3 design formed and welded into an assembly as discussed in detail in Section 5.1.2.7 below. In operation the fuel gas flows upward through the center and two outer manifolds formed by the holes on the long side of the plate. The gas flows through the slotted feed rails and into the distribution field. Then the gas flows over the main, corrugated rib field and out the exit distribution field and exit rails into the two intermediate exhaust manifolds. The cathode gas flows similarly, but on the other side of the plate.

The edges of the cell chamber are formed where the main rails, feed rails, and blocker rails press against the electrolyte matrix sheet, which extends to the outer edge of the cell (except for the manifold holes). The current collectors and electrodes fit within the rails and press against the electrolyte matrix.

5.1.2.3 MOD 2 IMHEX® Full-Area Separator (Bipolar) Plate Development

The separator plates for Stack MCP-4 were different from those used in Stack MCP-3. Hydraulic analyses, undertaken at ABB-CE, had indicated that the original manifold openings were too small and that cell-to-cell gas maldistribution would be experienced in tall stacks over about 100 cells. Consequently, the plate was again redesigned with larger holes for the gas manifolds. That redesign, together with other plate modifications, is discussed below.

The design of the MOD 2 separator plate was undertaken to provide larger, improved manifold areas for more uniform gas distribution, cell-to-cell, in stacks of 250 cells or more. The original MOD 1 design had a total open area, for each gas stream, of approximately 194 cm² (30 in²).

The MOD 2 plate was designed to increase the total manifold area, per stream, from 194 cm² to 645 cm² (30 in² to 100 in²) without any reduction in the active area per cell. The design was accomplished by increasing the width of the main plate sheet. The MOD 1 plate was pressed from 1000 mm (39.4 in) wide sheet; the MOD 2 design employed 1100 mm (43.3 in) sheet, the widest such sheet commercially available. All of the additional width was employed in increasing the manifold area; the active area of the plate remained identical to the MOD 1 design. The additional 50 mm (2 in) on each side changed the manifold shape from triangular to pentagonal for these now larger manifolds.

The new design resulted in a side benefit in the feed rails. In the old design, the slots exiting the feed rails at the acute corners of the manifold may have been somewhat starved. The new design permitted an increased number of openings into the feed rails and probably resulted in better gas distribution across the face of the cell quadrant. The number of exit slots from the feed rails to the distribution field remained the same, directly feeding gas into the grooves of the distribution field.

5.1.2.4 Detailed Hydraulic Analysis

5.1.2.4.1 Description of Physical System and Design Requirements

The Unocal Stack design consists of a pressure vessel containing an assembly of 250 cells of the IMHEX[®] MOD 3a configuration, discussed later. The MOD 2 and MOD 3a cell designs feature internal manifolds approximately 3.3 times larger in area than MOD 1 cells. The larger manifolds were specifically designed to be suitable for tall stacks, such as the Unocal stack, which have higher reactant flow compared to short stacks. Because the cells are assembled parallel to the ground, the reactant flow direction through the stack internal manifolds is vertical to the ground. The oxidant flow from the external system enters through a fabricated plenum which distributes flow to feed the three stack internal manifolds in parallel. Each of the internal manifolds distributes flow horizontally to the 250 cells in parallel. The flows exiting from the cells are collected by two parallel vertical stack internal manifolds which connect to the plenum and returns the flow to the external system.

The objective of this fluid analysis was to select a reactant distribution design which meets the design requirements of low pressure drop of less than 5.1 kPa (0.75 psi or 21" inches w.c.) and low reactant flow maldistribution, less than $\pm 10\%$. The pressure drop requirement is based on maintaining high wet seal, sealing efficiency and to minimize the parasitic power requirement of the facility. The small maldistribution requirement is based on reducing the magnitude of exit cell temperature variation which could increase corrosion at high gas exit temperatures and reduce cell performance at low gas exit temperatures.

Additional design requirement for uniform flow distribution within the assembly of cells is to eliminate flow restrictions in any one cell which could cause reactant starvation-resulting in a negative cell voltage with undesirable electrochemical reactions. This requirement is especially difficult on the fuel side because of the high fuel utilization required for system efficiency. On the oxidant side, this design requirement is equally important but less difficult to achieve because of the lower oxidant utilization resulting from high flow rates required for cooling the stack. More specifically, another design requirement is that the variation in dimensional tolerances from cell to cell be low enough so that the reactant utilization is never more than 90% in any cell in the stack.

An early objective of the design analysis of the 250 cell stack was to determine whether the MOD 2 manifold area was large enough to allow the selection of a simple, single-bottom-entry and -exit reactant distribution system that would meet the design requirements. A bottom-entry and -exit reactant distribution system is the design of choice compared to other alternatives, such as center cell feed or double end feed designs because of simplicity of construction, less vessel height, and lower cost. This issue was important because a preliminary analysis by ABB-CE had indicated that the manifold design might only be large enough to distribute to a maximum of 125 cells, necessitating the selection of a more complicated design such as a center feed system. As discussed in later sections, the results of this updated manifold analysis, using recently measured pressure drop data, indicated that a single-bottom entry and -exit distribution system design for 250 cells could easily meet the design requirements.

The design option for the external reactant distribution system is a plenum-type end plate. This design has the advantage of saving two or three feet of vessel height compared to conventional piping intensive designs. One requirement for this design is to avoid thermal transfer between the oxidant outlet and inlet streams. This can be accomplished by placing the inlet and outlet fuel gas within the end plate planform and manifolding the oxidant external to the end plate.

5.1.2.4.2 Analytical Model

A new manifold flow distribution model was developed to analyze the flow network of the internally manifolded 250 cell stack. This new module improved upon the original, ABB-CE analytical model by including more precise algorithms for local turning pressure losses and manifold stream momentum, and to add important new features such as natural convection, effect of dimensional tolerances, and friction factors for flow in irregular "bellows" shaped verticle manifold walls.

The analysis involved establishing the algorithms for the pressure variations from inlet to exit as a function of flow through each cell flow path in a multi-cell assembly which may be as small as 20 cells, or as large as 250 cells, for Unocal, or even greater for future designs.

The preferred design of a bottom reactant inlet and a bottom reactant exhaust was analyzed to compare against the design requirements discussed above. This design employs overall "U"-flow, in which the flow in the outlet manifold is countercurrent or reverse to the flow direction in the inlet manifold. It is known by fuel cell manifold designers that this is the preferred overall arrangement for flow distribution.

The pressure drop equations as a function of flow included nine major pressure losses through each flow path in the stack. The flow in each cell of the stack was iterated by solving a set of N non-linear simultaneous equations, where N represents the number of cells in the stack, until the pressure drop from manifold inlet to exit through each cell path was equal.

The nine pressure drop terms included in the model are listed below:

1. Inlet manifold stream momentum
2. Inlet manifold friction
3. Inlet manifold convection (gravity effect)
4. Manifold to cell inlet turn
5. Cell inlet to cell outlet
6. Cell outlet turn to collector manifold
7. Outlet collector manifold stream momentum
8. Outlet collector friction
9. Outlet collector convection (gravity effect)

This new mathematical model was applied to the Unocal 250-cell stack assuming the MOD 2 cell geometry and Bechtel "name plate" operating flow conditions. In performing this analysis, the

stack pressure drop as a function of flow correlation of Stack MCP-3 data was used for each half-cell pressure drop (item 5 in the list). This correlation was compared to data from the Stack MCP-4 test of MOD 2 cells. This comparison is shown in Figure 5.1-5. The correlation, based on Stack MCP-3 data, compares favorably with the Stack MCP-4 data; especially in the equivalent flow region anticipated for Unocal, the lower right corner of the figure. This confirms that the cell pressure drop correlation, based on Stack MCP-3, used in the oxidant side hydraulic analysis is valid.

As seen from Figure 5.1-6, the calculated estimate for flow maldistribution at the cathode varies from +5% at the bottom cell to -2% at the top cell. This maldistribution is sufficiently low that cooling problems in the stack are not anticipated. The anode flow maldistribution graph is similar.

5.1.2.5 Plate Production Schedule

The separator plates were made in three batches. The first batch was the MOD 1 design, used in Stack MCP-3. Stack MCP-4 was run with plates from the second batch, using the MOD 2 design. A larger batch of 370 plates provided the parts for Stacks MCP-5, MCP-6, MCP-7 (mock-ups), and the Unocal 250 cell stack. Additionally, several plates were consumed in testing and development of processing techniques.

5.1.2.5.1 Feed Rail Modifications

Stacks MCP-3, MCP-4, and MCP-5 employed positive fit-up, with the electrode surface slightly above the level of the wet seal rail to ensure good electrode/matrix contact. However, matrix integrity during preconditioning was an issue with these stacks. During start-up, the matrix/seal rail contact was not firm, resulting in matrix rupture and seal leakage. Consequently, Stack MCP-6 used slight negative fit-up, or the seal rails are pressed against the matrix during start-up. The stack operated well mechanically, with no loss of matrix. However, the stack pressure-drop climbed increased the test. During dismantling, it was found that the feed rails were collapsing.

Consequently a new feed system was developed. The original feed rails were removed and a series of stainless steel bars were welded in the feed locations. The electrodes and current collectors were extended to cover these bars, resulting in a series of gas feed channels formed by the gaps between the bars. For fabrication ease, a "comb" was cut to contain all the bars for one feed point, the bars were tack-welded in position, and the backbone of the comb was cut off. This modified separator plate was called MOD 3a. MOD 3b, used for the first stack after the Unocal operation, had the same hydraulic configuration, but with the ribs pressed into the feed locations.

CATHODE PRESSURE DROP **Test MCP-4**

Figure 5.1-5. Cathode Pressure Drop Data for Stack Test MCP-4

Figure 5.1-6. Calculated Cathode Flow Distribution for 250-Cell Stack

5.1.2.6 Separator Plate Specifications

The specifications for the separator plates are discussed below.

5.1.2.6.1 Main, Corrugated Plate Blank

The blank for the forming of the corrugated plate is made of Type 316 SS with 10% of the total thickness as nickel, on the anode side for corrosion protection. The specification for the plate is:

Thickness:	0.50 ± 0.05 mm (20 ± 2 mils)
Blank Size:	1100 x 1650 mm (43.3 x 65 in)

5.1.2.6.2 Main Rail Blanks

The main rails, which form the wet seals, are pressed from blanks of 316L SS. The nickel layer is not required; rather, the main rails are protected from corrosion in the stack by aluminizing, discussed in Section 5.1.2.7.3, Wet Seal Aluminization. The specification for the main rail blanks is:

Thickness:	0.70 ± 0.05 mm (28 ± 2 mils)
Blank Size	1100 x 1550 mm (43.3 x 61 in)

5.1.2.6.3 Feed Rails

The MOD 3 feed rails were cut from 1220 x 2440 mm (4 x 8 ft) sheets of 316L SS. Those feed rails that were to be used on the anode side of the separator plate were nickel plated on the underside to inhibit the catalytic action of the stainless steel for carbon formation. The nickel plating was applied after cutting, forming, machining, and masking. The specification for the material was

Thickness:	0.70 ± 0.05 mm (28 ± 2 mils)
Nickel Plating:	0.0125 mm (0.5 mils)

The feed rails were formed after cutting. The feed rail projection toward the active area contained 17 slots that were 4 mm wide x 1.25 mm high (157 mil x 50 mil). The slots were angled to feed directly into the 17 grooves (on the cathode side) or rows of orifices (on the anode side).

For the Unocal Stack, the feed rails were broken free of the plate, and the modified feed design of MOD 3a, discussed above, was installed.

5.1.2.6.4 Separator Plate Assembly

Each of the parts had a series of specifications throughout the manufacturing process — forming, cutting, welding, aluminizing, and heat treatment. After the final steps, however, three specifications are most important: the height of the corrugations in the ribbed area and the distribution fields, the overall thickness of the assembly at the wet seal area, and the "step height". These dimensions are indicated on the sketch of Figure 5.1-7.

The ribs in the corrugated area and the distribution fields support the current collectors, and hence the electrodes, while providing channels for the distribution of the reacting gases. The height of the ribs is a factor in calculating the overall fit-up of the cell.

The overall thickness of the wet seal rails — the main rails, the blocker rails, and the feed rails — defines the level of the electrolyte-soaked matrix in the operating cell. This is an important dimension because it defines the locations of the electrode faces.

The step height is the distance from the wet seal face to the level of the step, on the rails, that supports the current collector and electrode at the edge of the cell. As such, the level of the step should be the same as the level of the ribs on the face of the cell.

5.1.2.7 Separator Plate Construction and Continuing Development

5.1.2.7.1 Parts Pressing

Although the active area in the MOD 2 design was identical to that in the MOD 1 plates, the portion of the die set for the active area was not used in the new die. Rather, a completely new die set was machined. With this approach, the complete die set for the MOD 1 plates was maintained intact as a back-up position in the event of a mishap with the MOD 2 development.

The decision to make a complete new die set had an additional benefit. It permitted refinement of the die tooling features in an additional iteration to improve the pressing of the plates. For example, the plates for Stack MCP-3 had a pronounced wave pattern in the active area. This wave was caused by spring-back of the work-hardened material after forming. With the edges constrained, the growth in the lateral dimension was manifested as a wave in the plate. With the re-manufacturing of the die set for the MOD 2 design, this wave was nearly eliminated.

5.1.2.7.1.1 Design of Forming Dies

The MOD 2 die set was designed and manufactured by the plate pressing vendor because they had designed and built the dies for the 0.1 m² (1 ft²) separator plates and the initial MOD 1

Figure 5.1-7. Significant Dimensions for Fit-up on Full-Area Separator Plates

*Definition of Significant
Separator Plate Dimensions*

design. With this background, the vendor was well suited to improve upon the design of the dies. M-C Power engineers aided in this effort with on-site contributions in an iterative approach to die manufacture.

The vendor and M-C Power engineers added draw pockets in the waste area within each of the manifolds and around the outside of the plate as in Figure 5.1-8. The stretching of the metal, in these draw pockets, counteracted the stretching within the active area and was instrumental in minimizing the waviness of the plates. Figure 5.1-9 is a photograph of a pressing of the main separator plate, illustrating the draw pockets.

Except for the changes noted above, the dies for the MOD 2 design were quite similar to the ones for the original separator plates. They were still built of modular sections for ease of relieving, shimming, or replacement if necessary, after the prequalification of the dies. The main separator plate die was still a double-acting, male-and-female die-set; the main rail dies were single-acting.

5.1.2.7.1.2 The Forming Operation

M-C Power and the vendor engineers developed the pressing operation using a custom-engineered 30,000 metric ton hydraulic press. An iterative process of pressing, measurement, and adjustment was employed in trial pressings of all dies. Significant polishing, shimming, and relieving of the dies was required to produce plates that were relatively satisfactory. This effort yielded the initial plates for Stack MCP-4. Figure 5.1-10 is a photograph of an M-C Power engineer while he is hand-relieving a section of the bottom die. The same dies were used in the long plate production run that manufactured 370 separator plates for Stacks MCP-5, MCP-6, MCP-7, and the 250-cell Unocal stack.

The as-pressed plates for Stack MCP-4 were much flatter and more uniform than those produced earlier for Stack MCP-3. This stack exhibited a mean waviness of 3 mm (120 mil), measured by placing the sheet on a flat surface, placing a flat beam across the plate, and measuring the distance from the beam to the plate.

The construction of Stack MCP-4 indicated that this level of waviness was still unsatisfactory. Therefore, the long manufacturing run of 370 plates employed a double pressing, with intermediate annealing. The mean waviness of the plates was reduced to 1.6 mm (63 mils).

5.1.2.7.2 Cutting and Welding

The new, wider separator plates with larger manifold openings required new procedures and computer programs for cutting and welding, in addition to new cutting and welding fixtures. These were developed as discussed below.

Figure 5.1-8. Sketch Illustrating Draw Pockets on Full-Area Separator Plates

Figure 5.1-9. Photograph Illustrating Draw Pockets on Full-Area Separator Plates

Figure 5.1-10. M-C Power Engineer Hand-Relieving Separator Plate Dies

5.1.2.7.2.1 Development of the Cutting Process

The plate-cutting process had been satisfactory on the MOD 1 plates. Therefore, the same principles were employed in the development of this cutting system, although a new cutting fixture was required. The same vendor was employed with the same computer-controlled, 5-axis laser cutting head. In fact, the computer file for the CAD engineering drawing was fed directly into the laser computer for control of the cutting operation. However, significant development effort was required to determine the preferred head velocity, cutting angle, laser focal length, and laser power for rapid, clean, dross-free cutting. These data are stored on the Operation Sheets.

The clamping fixture was based on the fixture used for the MOD 1 plates, but adapted for the larger planform. The same fixture was used for both the main rail plates and the corrugated separator plates. It employed semi-automatic, pneumatic clamping of the plates. First, an alignment system was used to locate the plate within the fixture, employing the far corners of the plate manifold as fixed locating points. Then, internal clamps, through the manifold holes, were used to grip the plate while the laser cuts the outside dimensions of the plate. Additionally, the laser cut holes for locating the plates over dowel pins in the subsequent welding operation.

5.1.2.7.2.2 Development of the Welding Process

The welding operation was improved for the production of the MOD 2 separator plates. Clamping fixtures were made for both the spot-welding and continuous welding operation. These fixtures employed manual, over-center clamps. In both cases, the fixtures were machined from 50-mm (2-in) thick aluminum, with the fixture-plate relieved so that the clamping area was the feet of the main rails, without touching the wet seal area or the electrode-supporting step. The thick aluminum was used for uniform clamping and as a heat sink for rapid heat removal from the work. The heavier clamping fixture resulted in less thermal distortion of the separator plates during the welding process.

Figure 5.1-11 shows the spot-weld operation, with about 200 spot welds per plate. Figure 5.1-12 shows the continuous welding of the plate periphery. Like the cutting operation, the computer file for the CAD drawing was fed directly into the computer for controlling the welding operations. Again, the factors controlling the welding were developed iteratively for each 150 mm (6 inch) length of weld. These factors are recorded both on Operation Sheets and at the Engineering Department of M-C Power.

5.1.2.7.3 Wet-Seal Aluminizing

The last step in the manufacture of the separator plates is the application of an aluminum coating to the wet-seal surfaces. This aluminizing process is required because the molten carbonate is extremely corrosive to metallic materials at electrochemical voltages midway between the hydrogen and oxygen potentials, as would exist in all wet seal areas between the oxidant and fuel manifolds and at other locations. Aluminum, when applied to these areas, first forms an inert oxide and then lithiates to LiAlO_2 for protection of the metallic substrate.

Figure 5.1-11. Spot Welding the Separator Plates

Figure 5.1-12. Continuous Welding of the Separator Plates

IGT and ABB-CE had found that an adherent aluminum layer could be formed on a clean metal surface by thermal-spraying. The alloying was improved by vacuum heat-treating to enhance the diffusion layer.

The processes of plate masking, grit blasting, thermal spraying, and heat treatment were approximately the same for the MOD 2 plates as had been employed for the MOD 1 plates. These operations are highly labor-intensive, with significant manual processing for each step. Improved techniques were developed for aluminizing of production quantities of separator plates for the MCP-7 and PDT-1 efforts.

The four steps in this initial process are 1) masking the plates, 2), grit-blasting the exposed wet seal area, 3) thermal spraying, and 4) vacuum heat treatment of the parts.

5.1.2.7.3.1 Masking

Masking of the separator plate, prior to aluminization, is required to eliminate overspray, which would increase the electrical resistance of the cell. The masking operation is labor-intensive, requiring about three man-hours per plate. The tape is fiberglass-based, called Metco Flame Spray Masking Tape.

Before masking, the wet-seal surface and the adjoining areas are cleaned with acetone or alcohol-based solvent. The perimeter of the plate, along the outside edge of the wet seal, was masked. Similarly, the inside of the manifold openings was also masked to the inner edge of the wet seal. The main corrugated area was protected by plastic sheets, and the flame-spray tape was used to mask the distribution fields, up to the inner edge of the wet seal.

5.1.2.7.3.2 Grit-Blasting

Grit-blasting prepares the surface for aluminizing by removing the protective oxide film from the metal. The operation uses Metco grit-blasting equipment with a tapered-bore nozzle and 25 psi (172 kPa) air pressure. The grit used for Stack MCP-4 was silica-free aluminum oxide. Silica, if trapped in the part, would react with the molten carbonate. It was found that a slightly larger particle size grit resulted in a more uniform aluminum layer and this material was used on the production run. The operation takes about 15 minutes per plate.

5.1.2.7.3.3 Thermal Spraying

The aluminum coating, at 4 to 5 mil (1-1.25 mm) thickness, is applied to the wet-seal area by thermal spraying. The operation takes about 30 minutes per plate.

5.1.2.7.3.4 Heat Treatment

The aluminum film is bonded to the substrate by a diffusion layer formed during a short heat-treatment operation. This heat treatment, therefore, is a critical stage in the process.

The plates are first stripped of masking and cleaned with solvent (acetone or alcohol) to remove adhesive and any remaining grit from the blasting operation. The plates are hung from a fixture and bottom-loaded into an Abar Ipsen V6 vacuum furnace. This treatment was used for Stack MCP-4 and parameters were determined to be sufficient to start formation of the diffusion bonding layer but not result in warping of the plates.

5.1.2.7.4 Plate Quality Assurance

The measurement of the completed separator plates was done by QA/QC personnel at M-C Power using the CMM. The CMM is a device that automatically determines the x,y, and z coordinates of a given point, according to a preset computer program for specifying each point. The critical data were the total wet seal height, from the anode side to the cathode side, the step height, and the rib height relative to the step height. The plates approached the desired dimensional tolerances. Figure 5.1-13 presents the histogram for the overall wet seal thickness for Stack MCP-6, from the same production batch as the Unocal stack. For the wet seal thickness, about 89% of the data fall within the specification goals. These CMM data were acquired after the improved measurement techniques discussed below were developed.

The data from the CMM were compared with manual measurements, both from the original qualification of the die-set and taken at the time of the CMM measurement. Errors were found in both the CMM measurements (caused by tilting of the main rails during clamping) and in the manual techniques. These were resolved and the two measurement systems are now in general agreement.

5.1.3 Bench Scale Testing (BST) Development

5.1.3.1 Overview of Bench Scale (100-cm²) Cell Test Program

M-C Power undertook a testing program at the bench scale, primarily in support of the matrix development effort for the Unocal 250-cell power plant. As is discussed in Section 5.1.1, development of a preferred matrix, with proper pore size distribution, no roll compaction, and improved wet seal integrity, was a significant effort in this program. Each of the 20-kW, full-area stack tests employed a different matrix configuration, and these configurations were initially proved in the bench scale test (BST) program. Because this effort was in support of the matrix development program, the BST program was initially considered as part of the overall QA/QC effort.

The pressurized test stands were designed at M-C Power, as described in Section 3.2.3, Quality Control Component Evaluation Test Stand (CETS) of this document. Six stations were delivered to IGT for their R&D support effort and the other two were operated at M-C Power in the QA/QC program. The MCFC cells operated in the BST effort are nominally 10 cm X 10 cm (4 in x 4 in) for 100 cm² active area, and the tests are often described by one of these dimensions.

HISTOGRAM - MCP-6 PLATES TOTAL WET SEAL THICKNESS

Figure 5.1-13. Histogram of Wet Seal Height

The first pressurized bench scale cell tests were operated in January, 1993, concurrently with the 20-kW Stack MCP-4. This was also the time of active-component specification development and the process scale-up of continuous component tape casting and sintering for the Unocal 250-kW stack electrodes. Therefore, the BST testing was directed at the development of the Unocal matrix tapes for continuous casting and elimination of the roll compaction procedure. Also, two cells were run to evaluate the effect of known anode and cathode defects to determine the feasibility of using such electrodes in the Unocal 250-kW stack.

A more detailed description of the 100-cm² (15.5 in²) cell test stands is given in Section 3.2.3. A summary of the cells tested under this program is given in Section 5.1.3.2, below, and Table 5.1-1.

5.1.3.2 Summary of BST Cells Tested in the Unocal Project

Table 5.1-1 outlines the 100-cm² (15.5 in²) cell tests which were operated at M-C Power in the pressurized test stands. The purpose of the test is presented in the second column of the table, and a summary of the results or cause of failure is given in the last column. The first five cells (M0193001-M0193005) were primarily shake-down tests, in which the equipment was proof-tested and the cell testing and pressurization procedures were developed. All of the cell tests after the initial shake-down tests were operated at 3 atm (304 kPa) pressure with system gases (described later). The general operational guidelines developed are outlined below, including the post-test analytical procedures.

5.1.3.2.1 Standardized Bench-Scale Testing Procedures

5.1.3.2.1.1 Cell Components

The electrochemically active components for each cell were tape-cast and sintered using the production equipment at M-C Power. The cell components were taken from areas of the production sheets that did not interfere with full-area component cutting.

A carbonate loading spreadsheet program, similar to that utilized for the full-area stacks, was utilized to select carbonate tapes that would provide the design filling.

Upon completion of all reactions, the Li/K ratio was expected to be near the eutectic composition of 62% Li / 38% K.

5.1.3.2.1.2 Wet Seal Protection

The wet seal protection for the anode hardware was 0.05 mm (2 mil) aluminum, which has been standardized in the IGT effort. An exception was Cell M0193009, which employed a thermal-sprayed coating. Additional methods for aluminization of the wet seals are also in development.

Table 5.1 -1. Summary of Bench Scale Testing

Cell No.	Purpose	Cell Construction Features	Operating Conditions				Results
			Gas		Operating Hours	Pressure	
M0192-001	Test stand design shake-down	MCP-4 Twin Cell	Reference tem (dry)	Sys-	660	1, 2, 3 Atm	Operation of stands to 3 ATM of pressure verified. Identified problems with clamping device seal design and cell power wiring.
M0193-001	Evaluate compliant matrix sets for Stack MCP-5 specification.	Standard baseline anode and cathode with unrolled outer matrix layers.	Reference tem (wet)	Sys-	420	1 Atm	Terminated after two losses of process air during operation. Second loss of air decreased cell performance.
M0193-002	Evaluate compliant matrix sets for Stack MCP-5 specification.	Standard baseline anode and cathode with partially rolled outer matrix layers.	Reference		200	1 Atm	Terminated after loss of process air during operation. Cell performance decreased after this loss.
M0193-003	Evaluate compliant matrix sets for Stack MCP-5 specification.	Standard baseline anode and cathode with partially rolled outer matrix layers.	Reference tem (wet)	Sys-	312	1 Atm	Terminated after accidental overfill of cathode humidifier injected water into cell
M0193-004	Evaluate compliant matrix sets for Stack MCP-5 specification.	Standard baseline anode and cathode with unrolled outer matrix layers.	Reference tem (dry) System (wet)	Sys-	1290	1, 2, 3 Atm	Thermal cycle during upgrade of building electrical system. Low performance after thermal cycle.
M0193-005	Evaluate compliant matrix sets for Stack MCP-5 specification.	Standard baseline anode and cathode with partially rolled outer matrix layers.	Reference tem (wet)	Sys-	435	1, 2 Atm	Fuel leak caused by cracked weld on anode humidifier oxidized anode.
M0193-006	Stack MCP-5 Twin Cell for: 1. Engineering model 2. Vessel purge gas evaluation 3. Component evaluation	Standard baseline anode and cathode with partially rolled outer matrix layers.	Reference tem (dry) System (wet)	Sys-	895	1, 2, 3 Atm	Fuel leak across fuel inlet wet seal resulted in an oxidized anode.

M0193-007	Stack MCP-5 Twin Cell for: 1. Engineering model verification 2. Vessel purge gas evaluation 3. Component evaluation	Standard baseline anode and cathode with partially rolled outer matrix layers.	Reference Sys- 696 tem (dry) System (wet)	1 Atm	Terminated after accidental overfill of cathode humidifier injected water into cell. Cell was operated for 250 hours after this event.
M0193-008	Stack MCP-6 Twin Cell for: 1. Component verification 2. Wet seal protection evaluation	Standard baseline anode and cathode with matrix layers of unrolled lower porosity tapes. Foil wet seal protection.	Reference Sys- 2283 tem (wet)	1, 3 Atm	Excessive amount of large matrix pores unable to retain carbonate. Carbonate consumption from corrosion of anode wet seal.
M0193-009	Stack MCP-6 Twin Cell for: 1. Component verification 2. Wet seal protection evaluation	Standard baseline anode and cathode. Low porosity non-rolled matrix layers. Thermal sprayed aluminum wet seal protection.	Reference Sys- 1254 tem (wet)	1, 3 Atm	Low matrix carbonate inventory. Low Ni dissolution.
M0194-001	Evaluate defects in production electrodes.	Standard baseline anode and cathode. Low porosity non-rolled matrix layers. Foil wet seal protection	Reference System (wet)	416 1 Atm	Low cell performance due to electrode defects.
M0194-002	Evaluate thinner electrodes and current collectors for MOD 4 design.	Low chrome anode. High pore MPS cathode. Foil wet seal protection.	Reference System (dry) System (wet)	1274 1, 3 Atm	Terminated due to increased cell iR. iR increased due to carbonate loss from failed anode wet seal.

5.1.3.2.1.3 Cell Assembly and Fit-up

The cells were constructed with an anode end plate using the narrow-rib pattern developed at M-C Power. The anode and cathode current collectors used the same hole pattern and spacing as the full-area cells. Generally, a flush fit-up was utilized on the anode flange, but a +0.04 mm (+1.6 mil) cathode fit-up. This positive fit-up differs from the full area stack fit-up, which is now negative. On the bench scale cells, fit-up must be slightly positive to accommodate the hard wet seals, which do not compress under axial load like the full-area cells.

During assembly, component dimensional data, component compositions, and porosity were recorded for all the components used for test cell construction. For each cell, these data are contained in a package of assembly worksheets completed during cell construction.

5.1.3.2.1.4 Cell Conditioning

The standard cell conditioning and start-up schedule, which was developed under this program was used for the bench-scale cells. During cell conditioning, both the anode and cathode humidifiers contained water at ambient temperature.

5.1.3.2.1.5 Steady State Operation (Load)

Steady state operation was conducted using the standard gas compositions shown below in Table 5.1-2. A summary of the standard steady state operating procedure is presented in Table 5.1-3. After completion of about 200 hours of cell operation and baseline testing, the oxidant was changed to Systems Oxidant (SO-1) dry (no humidification). Then the humidification system was heated for SO-1 wet conditions.

At about 275 hours of operation the cells were pressurized to 3 atm (304 kPaa). The tests remained at 3 atm (304 kPaa) system conditions until test termination. The basis for test termination was that the endurance goals had been achieved or the cell suffered a > 15 mV loss in cell performance over a 24 hour period.

5.1.3.2.1.6 Polarization Tests

The procedure used for conducting this test was to increase the DC load current in steps from zero current, or OCV, to 16 A (160 mA/cm^2). Typically, during these tests, the gas flows to the cell are 75% fuel utilization and 40% or 50% oxidant utilization at 16A. A comparison of polarization tests conducted with reference and system oxidants at both 1 and 3 (101 and 304 kPaa) atm were generated for each cell. The number of polarization runs completed was a function of the cell life. Generally, polarization tests were completed after pressurization and every 500 hours thereafter. A final polarization run was completed prior to cell termination.

Table 5.1-2. Standard Gas Compositions

(Mole %)	H ₂	CO ₂	O ₂	N ₂	H ₂ O
SF-1	60	15			25
RO-1		30	14.7	55.3	0
SO-1		8	8	58	25

5.1.3.2.1.7 Fuel Utilization Tests

The purpose of this test is to evaluate the effect of fuel utilization on cell performance at a constant current density and oxidant utilization. This test provides an indication of the degree of anode polarization and uniformity of gas flow distribution across the face of the anode. Nernst effects, alone, will cause a variation of potential with fuel utilization of about 1 to 1.6 mV per percentage point change in utilization, over the range of about 40% to 70% utilization. Any greater variation is an indication of one of the issues above. Data are also obtained on how the components will perform at other than standard steady state operating conditions.

These tests were conducted at 160 mA/cm² (149 A/ft²) with $U_{t_{CO_2}}$ held constant. The anode gas flow is adjusted to obtain the required fuel utilization. A comparison was made of tests conducted at 1 and 3 atm (101 and 304 kPaa). Generally, fuel utilization tests were completed after pressurization and at every 1000 hours. A final fuel utilization run was completed prior to cell termination.

5.1.3.2.1.8 Oxidant Utilization Tests

The purpose of this test is to evaluate the effect of CO₂ utilization on cell performance at a constant current density and fuel utilization. This test provides an indication of the magnitude of cathode polarization and of the uniformity of gas flow distribution across the cathode. Data are also obtained on how the components will perform at other than standard steady state operating conditions.

These tests were conducted at 160 mA/cm² (149 A/ft²) with $U_{t_{fuel}}$ held constant at 75%. The cathode gas flow is adjusted to obtain the required CO₂ utilization. A comparison was made of tests conducted at 1 and 3 atm (101 and 304 kPaa). The effects were measured as a function of gas composition and cell life.

Table 5.1-3. Summary of Steady State Operation

Start-Up	Standard procedure			
0 - 2 hr	Cell Temperature: 650 °C (1200°F) Oper. Pressure: 1 atm (101 kPaa) Clamping Pressure: 25 psi (172 kPa) Load Current: 5 A	Fuel: SF-1; $U_{t_{fuel}}$ 60% at 16 A Oxidant: RO-1; $U_{t_{CO_2}}$ 50% at 16 A Vessel: N ₂ 98%, CO ₂ 2%		
3 - 21 hr	Cell Temperature: 650 °C (1200°F) Oper. Pressure: 1 atm (101 kPaa) Clamping Pressure: 25 psi (172 kPa) Load Current: 10 A	Fuel: SF-1; $U_{t_{fuel}}$ 60% at 16 A Oxidant: RO-1; $U_{t_{CO_2}}$ 50% at 16 A Vessel: N ₂ 98%, CO ₂ 2%		
22 - 189 hr	Cell Temperature: 650 °C (1200°F) Oper. Pressure: 1 atm (101 kPaa) Clamping Pressure: 25 psi (172 kPa) Load Current: 16 A	Fuel: SF-1; $U_{t_{fuel}}$ 60% at 16 A Oxidant: RO-1; $U_{t_{CO_2}}$ 40% at 16 A Vessel: N ₂ 98%, CO ₂ 2%		
	Tests:	<ol style="list-style-type: none">1. One (1) polarization test with fuel flows set for $U_{t_{fuel}}$ 75% at 16 A.2. One (1) fuel utilization test 50%, 60, 70%, 80% at 16 A.3. One (1) Oxidant utilization test 30%, 40%, 50% at 16 A.4. IR test at 16 A steady state conditions.		
190 - 216 hr	Cell Temperature: 650 °C (1200°F) Oper. Pressure: 1 atm (101 kPaa) Clamping Pressure: 25 psi (172 kPa) Load Current: 16 A	Fuel: SF-1; $U_{t_{fuel}}$ 60% at 16 A Oxidant: RO-1 (dry); $U_{t_{CO_2}}$ 40% at 16 A Vessel: N ₂ 98%, CO ₂ 2%		
217 - 271 hr	Cell Temperature: 650 °C (1200°F) Oper. Pressure: 1 atm (101 kPaa) Clamping Pressure: 25 psi (172 kPa) Load Current: 16 A	Fuel: SF-1; $U_{t_{fuel}}$ 60% at 16 A Oxidant: SO-1; $U_{t_{CO_2}}$ 40% at 16 A Vessel: N ₂ 98%, CO ₂ 2%		
	Tests:	<ol style="list-style-type: none">1. One (1) polarization test with fuel flows set for $U_{t_{fuel}}$ 75% at 16 A.2. One (1) fuel utilization test 50%, 60, 70%, 80% at 16 A.3. One (1) Oxidant utilization test 30%, 40%, 50% at 16 A.4. IR test at 16 A steady state conditions.		
272 - 1274 hr	Cell Temperature: 650 °C (1200°F) Oper. Pressure: 3 atm (304 kPaa) Clamping Pressure: 25 psi (172 kPa) Load Current: 16 A	Fuel: SF-1; $U_{t_{fuel}}$ 60% at 16 A Oxidant: SO-1; $U_{t_{CO_2}}$ 40% at 16 A Vessel: N ₂ 98%, CO ₂ 2%		
	Tests:	<ol style="list-style-type: none">1. Four (4) polarization tests with fuel flows set for $U_{t_{fuel}}$ 75% at 16 A.2. Four (4) fuel utilization tests 50%, 60, 70%, 80% at 16 A.3. Four (4) oxidant utilization tests 30%, 40%, 50% at 16 A.4. Four (4) IR tests at 16 A steady state conditions.5. Two (2) GC analysis with dry outlet flow measurement.		
1200 + hr	Repeat 272-1274 tests every 500 hours			

5.1.3.2.1.9 Internal Resistance Measurements

The procedure used for conducting this test is to generate a nearly instantaneous interruption of the cell's DC load current and observe the voltage response. This voltage response is recorded using a digital storage oscilloscope. The measured immediate voltage change, caused by the direct resistance mechanism of the test cell, is then divided by the change in current. The resistivity of the component package, expressed as $\Omega\text{-cm}^2$, is a function of matrix thickness, contact resistance, ohmic resistance of the NiO cathode, and a number of other factors. Gas compositions, diffusion effects, and other longer term impedances are not included in the resistivity.

5.1.3.2.1.10 GC Analysis and Dry Outlet Flow Rates

Gas chromatograph measurements were taken from the outlet gas with the cell at steady state conditions. In addition, the total dry gas flow rate from both the anode and the cathode were measured. The measured outlet gas compositions and flows were compared with the calculated outlet values, based upon electrochemical utilization. These data were utilized for mass balance and failure mechanism analysis; e.g., Ni shorting, matrix cracking, wet seal failure, etc.

5.1.3.2.1.11 Post Test Analysis

Visual inspection of the cell's exterior was made to determine if significant corrosion or carbonate loss had occurred. During disassembly, the adherence of the cell layers to each other was noted as an indication of the contact of the components and whether the components were sufficiently filled with carbonate. The inside of the flanges were examined and any observed carbonate was recorded on the post test visual inspection data sheets.

After the cell was initially installed in the test stand, with axial clamping force applied, the distance between each corner of the heater plates was measured and recorded. The same measurement was repeated before removal of the cell to determine an overall cell shrinkage.

Following visual examination of the cell components, post-test thicknesses are measured and samples are selected for chemical analysis. Chemical analysis and post-test porosimetry are utilized to determine:

- ▶ Carbonate inventory or final percentage fill of all components
- ▶ *In-situ* microstructural changes of the anode and cathode
- ▶ Ni dissolution or the amount of Ni transported to the matrix

5.1.3.2.2 Unocal Matrix Experiments

As part of the effort to define the Unocal unrolled matrix microstructure, cell tests M0193006 through M0193009 were run with roll compacted and unrolled matrices. The development of these

microstructures is further discussed in Section 5.1.2.3, MOD 2 IMHEX® Full-Area Separator (Bipolar) Plate Development.

Cell tests M0193006 and M0193007 were operated with Stack MCP-5 matrix configuration: higher porosity outer matrices with a low porosity inner matrix for good carbonate retention and as an effective barrier to gas crossover. As indicated in Table 5.1.1, both tests were terminated due to equipment difficulties. Cells M0193008 and M0193009 contained and validated the matrix configuration used in the Unocal stack.

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5.2 Subtask 5.2 Manufacturing Issues

Objective:

To obtain satisfactory separator plate life and performance by out-of-cell evaluation of materials and coatings for active area wet seal corrosion protection and evaluation and/or development of alternative joining techniques.

To utilize the technologies developed under this subtask to manufacture separator plates for use in full-area cell stack tests and in the 250 kW power plant test.

To fabricate full-area components to improve manufacturing techniques and to provide components required for the assembly of the full-area stack tests.

Discussion:

The subject of "Manufacturing Issues" is not readily separated from the "Engineering Issues" discussed in Section 5.1 of this document. Areas that could be presented here are discussed in Sections 2.5, Design, Fabrication, and Assembly of Full-Scale, Full-Height 250- kW MCFC Stack Module and 5.1, Engineering Issues, and are not repeated here.

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5.3 Subtask 5.3 Assembly Issues

Objective:

To identify the issues associated with the handling of large area, thin components and evaluate the equipment necessary for their storage and handling.

Discussion:

5.3.1 Identification of Issues Associated with Handling Large-Area, Thin Components

The two major handling issues identified are

- ▶ the ability to store both electrolyte matrix tapes over long time periods without drying out, and
- ▶ the ability to transport and store all work-in-process components.

5.3.2 Evaluation of Equipment for Storage and Handling of Thin Components

As support to Subtask 5.3.1, the solutions to these issues were:

- ▶ To place the uncut and cut electrolyte matrix components in vapor barrier bags which are impermeable to moisture. Five containers of desiccant are then placed into the bags which are then purged with nitrogen to eliminate air from the bags and then the bags are heat-sealed. After sealing, the bags are stored on horizontal storage shelves in the dry room.
- ▶ To procure storage racks for the dry room to store electrolyte matrices and to procure storage racks for the 7900 building to store anodes and cathodes.

5.3.3 Detailed Design of Stack Assembly Area

Prior to manufacturing and assembly, a Flow of Material analysis of the stack assembly area was completed. The results of the analysis prompted a solution to transporting the stack from the dry room assembly area to the ATF and then from the ATF to a location external to the manufacturing area where the conditioned stack could be loaded into the bottom of the pressure vessel.

The solution was an "air bearing" concept. To transport the assembled stack from the dry room assembly area, an air bearing cart, capable of "floating" and steering the stack from the stack assembly area to the ATF and then out to the portable dock was designed and built. An "air bearing"

consists of a thin, continuous cushion of air at low pressure applied over a relatively large area. Directional control is provided by two synchronized drive wheels controlled by dual pendants.

The stack assembly is built on top of the air bearing cart and then transported to the ATF. After testing, the stack assembly is placed back onto the air bearing cart and then transported to a portable dock extending from the building into the parking lot. The stack is then picked up, using a portable crane, off of the air bearing cart and then placed into the bottom of the pressure vessel.

5.4 Subtask 5.4 Cost Issues

Objective:

To verify and scale-up copper-based anodes which resulted from initial development under EPRI Contract No. RP-3059-2 and to continue evaluation and development of binder systems which will ease start-up requirements and times.

Discussion:

5.4.1 Materials Cost Reduction

This effort is further divided into subtasks. Research into lower-cost components was undertaken at IGT. Engineering development and manufacturing cost-reduction was the responsibility of M-C Power. The original program plan anticipated the engineering and manufacture of the separator plates by Combustion Engineering. With the program reorganization, however, this responsibility fell to M-C Power. Cost reduction in this area is also presented.

5.4.1.1 Lower Cost Anodes

Objective

The objective of this subtask was to develop a cost effective copper-based anode.

Summary

A copper alumina anode that showed good promise in studies under a previous EPRI-funded project (EPRI Contract RP-3059-2) was selected for continued development under this program. This anode showed good creep resistance in out-of-cell creep testing and encouraging cell performance in a 3-cm² (0.46 in²) cell. Preparation of the copper-based powder was performed by a vendor using a proprietary method. In discussions with the vendor, it was determined that the projected cost of the powder was prohibitive. Testing of this anode proceeded to determine the technical potential of copper-based anode materials and to evaluate the use of less-expensive starting powders.

The copper alumina anode that was previously tested in 3-cm² (0.46 in²) cells with promising results, failed to operate successfully in 100-cm² (15.5 in²) cells. It showed substantial creep under bench-scale operating conditions. This creep resulted in poor contact with the other cell components. In an attempt to maintain contact with other components, edges of the copper alumina anode were protected with a frame of LiAlO₂ tape and then assembled in the fuel cell with the edges extended to the wet seal. In this particular cell, there were cracks in the cathode, and copper was found in the matrix which shorted the fuel cell. This anode composition, therefore, is not a viable anode material under the conditions tested.

5.4.1.2 Lower Cost Start-up Binder Formulations

Objective

To develop a low cost binder system for electrolyte matrix tapes with clean and low temperature removal characteristics.

Summary

Before this subtask was initiated, IGT's electrolyte matrix tapes were prepared using a proprietary binder mixture that was manufactured by a supplier. Not only was this binder costly, its specific composition was not known and modifying it to suit various matrix and carbonate compositions involved unacceptable guesswork. A binder system was therefore developed from a commercially available polymer with a wide market and low cost. This system uses environmentally-acceptable solvents and is removed cleanly at low temperature. This binder system was used to manufacture the tapes used in Stack IGT-6, and the technology has been transferred to M-C Power.

5.4.2 Documented Separator Plate Costs

Table 5-4-1 lists the relative separator plate costs, by unit production area, for the three modifications of the full-area separator plate that were designed and/or manufactured during the course of the program. The MOD 1 separator plates were employed in Stack MCP-3 and were quickly redesigned to the MOD 2 plates with larger manifolds and, therefore, capability of taller stacks with acceptable cell-to-cell gas distribution. The MOD 2 separator plates were a production run of enough plates to test Stacks MCP-4, MCP-5, MCP-6, mock-ups for MCP-7, and the foundation for the Unocal stack. The actual plates employed for the Unocal stack were called MOD 3a, a redesign occasioned by the results of Stack MCP-6, as discussed elsewhere in this document

MOD 3b plates were a production run of the first redesign following the results of Stack MCP-6. The plates were manufactured during the construction of the Unocal stack, and the costs are a matter of record. The MOD 4 plates were designed during this period, and the costs are based on vendor quotes.

The costs of the MOD 1 separator plates are not included above because these are for a design which cannot service the market entry design requirements and, as the first prototype, the costs are very high and less instructive. Although the nickel-coated stainless steel for that batch was purchased in tonnage quantity (in anticipation of additional manufacture), each of the unit operations was a development effort and contained the costs associated with the initial set-ups and learning.

Table 5-4 - 1

Separator Plate Cost Reduction

Normalized Costs per Plate (Mod 2 Plate Cost as the Baseline)

	MOD 2	MOD 3	MOD 4
Ni Coated Main Plate Material	0.136	0.143	0.090
Plate Pressing	0.309	0.115	0.053
Plate Cutting and Welding	0.272	0.206	0.065
Feed Rails	0.177	0.000	0.000
Plate Aluminizing	0.106	0.066	0.054
Total	1.000	0.530	0.262

After the first, MOD 1 plates, the costs have dropped dramatically with each production run of plates, even without realizing additional savings in the raw material. Better and faster techniques were developed from manufacturing engineering with each iteration of the plates, resulting in reduced costs in each manufacturing area.

These documented cost reductions lend credence to the assumptions inherent in the manufacturing cost study, described below.

5.4.3 Updating of Manufacturing Cost Study

M-C Power's strategy for commercialization recognizes that the corporation must be in a position to provide a power plant at cost-competitive prices, but at market entry volumes. Thus, having information relative to very high volume manufacture is not sufficient to guarantee the viability of a commercial entity in the "market entry" or "middle market" phases of its commercial existence. Those phases may be in the production range of 30 to 50 megawatts (MW) per year.

In an attempt to clarify the understanding of manufacturing costs relative to different volume production levels, M-C Power embarked on a program to develop a software tool that would allow the evaluation of various manufacturing scenarios, at different volume levels, and hence the different years in the commercialization activity. This tool, called the Executive Cost Control System, incorporates: 1) inputs relative to the design and technology assumptions based on the development

program, and 2) inputs so that real general ledger accounts, overhead and burden structures are also incorporated into the model.

This model has been validated based on present factory performance associated with both the Unocal and NAS Miramar project activities. The program is interactive and permits the evaluation of bottom line dollars per kilowatt manufactured costs given technology assumptions, factory running assumptions, staffing and general ledger accounts, capital equipment usage, and staffing for the manufacturing lines.

The results of various studies are contained in a detailed report labeled "M-C Power Competitive Costs." Cases studied include the production of Unocal-type power plants in the present time period and have evolved to show the manufacture of the NAS Miramar stack, an advanced technology stack, market entry stacks, and further test market entry conditions out to 250-300 MW per year production level.

The results confirmed the viability of the technology and have been used by M-C Power to focus on the non-recurring development activities associated with targeting areas for likely and necessary cost reductions.

The Unocal evaluation shows that the largest areas of concern now are the separator plates and non-repeat parts. Both areas require a 20 to 30 times cost reduction from the Unocal values. The development programs are in place to address these issues and improvements relative to the San Diego project and planned demonstration projects are on track for improving these items to the degree necessary for a commercial business.

One important feature of this program is that it evaluates costs based on the continuous manufacturing use of the various technologies with the present staff and equipment and general ledger accounts as they exist. It is not a one-time cost for a single unit manufacture such as the Unocal power plant. This puts the evaluation on a constant and uniform comparison basis for present day and market entry and high volume production operations.

This software tool has been installed on computers throughout M-C Power's engineering and manufacturing organizations from engineering to supervisor and management levels. The use of this tool has allowed M-C Power to focus clearly on items with maximum return for commercialization benefit and has resulted in significantly streamlining the research and development activities associated with cost reduction objectives.

5.5 Subtask 5.5 Full-Area, Subscale Stack Tests in Support of Engineering, Manufacturing, Assembling, and Cost Issues Resolution

Objective:

To conduct a 20-kW full-area stack test under GRI sponsorship and three, 20-kW full-area stack tests in support of engineering, manufacturing, assembling, and cost issues resolution.

Discussion:

5.5.1 General

Topics of general background to all stack tests at M-C Power are discussed in this subsection of the document.

5.5.1.1 Introduction

Prior to the term of the present DOE Contract No. DE-AC21-90MC27394, previous work had been undertaken under GRI, EPRI, and DOE contracts at both IGT and M-C Power. IGT had patented the IMHEX® concept scaled up the active component production by a factor of 10 (from 100 to $\approx 1000 \text{ cm}^2$ [0.1 to 1 ft^2]), and designed the sub-scale separator plates. As discussed in Section 5.1.2, Design, Engineering, and Manufacture of the IMHEX® Separator Plates, that separator plate was the basis for the design of the full-area separator plate employed in the stacks numbered MCP-3 and higher. IGT developed the initial techniques for plate pressing, laser cutting, and laser welding of the plates.

IGT funded, through a subsidiary called GDC Corp., the construction of the sub-scale test facility, used in IGT's testing of sub-scale stacks. IGT operated a series of five stack tests, of varying numbers of cells, prior to M-C Power's initial sub-scale stack tests. The first of IGT's stacks did not perform well, primarily due to difficulty of dimensional control on the first-issue separator plates but also partially because of the initial scale-up of the active components. However, performance improved in each succeeding stack such that, by the fifth stack, the performance of the better cells essentially duplicated that of the bench-scale test ("Twin Cell") operating with similar components. The stacking techniques, fit-up assessments, and other issues that are encountered in operating stacks, rather than electrochemical bench-scale cells, all fed into the M-C Power full-scale stack testing effort under this contract.

The first M-C Power stack, named Stack MCP-1, was funded by GRI. It was a team effort with IGT for technology transfer. A 20-cell, sub-scale IMHEX® stack was fabricated and assembled at M-C Power's facility in Burr Ridge, Illinois and operated at IGT's stack testing facility on the southwest side of Chicago. The purpose of Stack MCP-1 was to act as the test bed for components, techniques and procedures to be used in the upcoming 70-cell, tall stack test. The objectives of Stack MCP-1 were to: test an improved-strength matrix; eliminate the bubble barrier; and test an improved-aluminum coating on the wet seal rail.

Stack MCP-1 operated well and showed progressively better performance with time. It was voluntarily terminated. It withstood system upsets and recovered, demonstrating the resiliency of the design. Good gas sealing was achieved, validating the IMHEX® concept. The performance of the better cells in the stack was similar to that of the bench-scale test (the "Twin Cell") that employed similar components.

Stack MCP-2 was funded by EPRI and was directed at proving that the IMHEX® design was immune to "carbonate pumping," a phenomenon that plagues alternative MCFC design configurations and causes premature stack failure.

A 70-cell, sub-scale ($\approx 1000 \text{ cm}^2$ or 1 ft^2) IMHEX® stack was fabricated, assembled, and operated at MCP's stack testing facility. This was the first use of M-C Power's test facility that was constructed under the prior DOE contract DE-AC21-88MC25026.

The main purpose of Stack MCP-2 was to evaluate carbonate pumping, if any, in IMHEX® stacks. The objectives of Stack MCP-2 were to test the IMHEX® stack design at 1 atm with a larger number of cells and to test improved components.

Several modifications were made over Stack MCP-1:

- ▶ The plate reproducibility had improved sufficiently that all electrodes and current collectors were cut to the same size and shape.
- ▶ A new approach was used for adjusting the active area component fit-up.
- ▶ Four materials were used for the plates in the stack:
 - 316SS plain,
 - 316SS Ni-coated,
 - 310SS plain,
 - 310SS Ni-coated.
- ▶ Cell thermocouples were included in the stack on the cathode side of cells.
- ▶ The manifold area for the cathode gases in the plates was increased.

The key accomplishments of Stack MCP-2 are:

- ▶ All test objectives were achieved.
- ▶ The IMHEX® MCFC concept was verified in the 70-cell stack.

- ▶ Specific power of 135 mW/cm² (125 W/ft²) was obtained on a fuel containing 35% H₂ at a current density of 160 mA/cm² (149 A/ft²).
- ▶ Performance of 58 of the 70 cells in the stack was higher than 640 mV at 160 mA/cm², greater than 102.4 mW/cm² (95 W/ft²) at 75% fuel utilization.
- ▶ Performance of the 25 best cells in the stack was equal to or higher than the bench-scale twin cell performance: 746 mV at 160 mA/cm², 119.4 mW/cm² (111 W/ft²) at 75% fuel utilization.
- ▶ No carbonate pumping from the cathode end of the stack to the anode end was observed after 1275 hours of testing; thus validating the immunity of the IMHEX[®] concept to this phenomenon.

5.5.1.2 Fuels and Oxidants

The fuel gas employed in most of the full-area stack tests was a 4/1 mixture of hydrogen and carbon dioxide, humidified to 25% water concentration. This mixture simulates the fully-shifted output of a natural gas reformer operating at a steam/carbon ratio of 3.5. This gas is similar to the laboratory gases employed at IGT for many years and avoids the complications of handling carbon monoxide. It is known that the gas shifts rapidly over the nickel catalyst in the MCFC to approximately the following composition:

Species	Conc. %
H ₂	53.27
CO	6.73
CO ₂	8.27
H ₂ O	31.73

The fuel gas flows were generally set for either 60% or 75% utilization of both fuel gas species (H₂ and CO) at 1600 A (~ 150 mA/cm²) current draw. In some tests, the fuel gas was diluted with nitrogen. This dilution was employed for one of two reasons. First, the increased flow rate improved cell-to-cell gas distribution, enabling recovery of cells that are marginally starved. Alternatively, the dilution may be employed to thermally dilute any fires that would occur if there is a fuel leak overboard.

Two types of oxidant were employed. "Diagnostic" gas consisted of 70% air and 30% CO₂. This is the laboratory mixture that has been employed at IGT for many years. The alternative oxidant employed in the full-area stack testing is called "system" gas. It contains 8% each of O₂ and CO₂ in nitrogen. This is the oxidant composition that will be present in a natural gas MCFC system when the overall air fed to the system is 170% of stoichiometric requirements and cathode exhaust is recycled to the cathode inlet for stack cooling. The system oxidant is much weaker than the

diagnostic gas and the voltage penalty is about 86 mV per cell at 1600 A. Alternative techniques for stack cooling are being developed to partially recover this voltage loss, but they were not yet available for the Unocal stack.

The fuel and oxidant streams were generated by blending, using rotameters for flow control. The fuel is generated from cryogenically-stored liquids with metered water injection into the hot gas for control of the steam content. The oxidant is generated from liquid CO₂ (and N₂ if necessary) using compressed air as a source of O₂.

5.5.1.3 Original Program Plan and Modifications

The initial M-C Power response to DOE's PRDA anticipated the operation of four, full-area stacks — one at 10 cells, two at 20 cells, and one at 50 cells. At GRI's request, the size of the first stack was increased to 20 kW.

The last stack was planned to be 50 kW. It was to have been conditioned and initially operated at the M-C Power facility, as upgraded and pressurized under Task 4.2.2, and then shipped and operated at the Pico Rivera site of the Southern California Gas Co. These plans were suspended when the budget required for the 50-kW facility were assigned to construct the acceptance test facility. Therefore, the 50-kW test facility was not built, and the last stack was also sized for 20 kW, consistent with the available test stand.

5.5.2 Stack MCP-3

M-C Power operated its first full-area MCFC stack, under GRI funding, in April - July, 1992. That stack test, called Stack MCP-3, was quite successful, meeting all of the test plan goals, generating data for the design of demonstration-scale stacks, and indicating the direction for further MCFC performance gains. A topical report¹ for GRI was prepared that discussed the stack test in detail; that report should be referred to for a more complete discussion.

The M-C Power MCFC design is unique in this country and permits several advantages over the competitive power plant systems. The M-C Power Commercialization Plan calls for scale-up of the technology to large-area cells and the assembly of these cells into power plant stacks. Stack MCP-3 was the first step in the testing of the full-area stacks.

Stack MCP-3 was rated at 20 kW and contained 19 cells with an active area of 10570 cm² (11.37 ft²) each. Operating at atmospheric pressure, the stack delivered a maximum power output of 22 kW, and this power was only limited by the current-carrying capacity of the test facility, not the MCFC stack itself. Figure 5.5-1 presents the polarization and power curves for this stack operating on diagnostic gases. The stack achieved state-of-the-art electrochemical performance,

¹Scropo, J. A. "DESIGN, DEVELOPMENT AND EVALUATION OF NATURAL GAS-FUELED CFC CO-GENERATION SYSTEM" Topical Report for Subtask 3.3.2 Stack Testing 20 kW Full-Area, March 1994

**POLARIZATION & POWER CURVES
STACK MCP-3**

Diagnostic gases

Figure 5.5-1. Polarization Curves for Stack MCP-3

duplicating the cell potential that has been achieved on the bench scale, but with a scale-up factor of 100. Excellent cell-to-cell performance uniformity was achieved. The standard deviation of the cell potentials was about 15 mV at 1200 A ($\sim 114 \text{ mA/cm}^2$ or $\sim 106 \text{ A/ft}^2$); only 11 mV when cells with end effects were discounted. Figure 5.5-2 illustrates the uniformity of cell voltages, along with the predicted voltages based on a computer model developed from the results of bench-scale testing.

The total operating time exceeded 1256 hours, including over 300 hours of operation on dilute oxidant gases similar to those expected in a full-scale, methane-fueled system with cathode recycle for stack cooling. Two thermal cycles were performed without loss in performance.

The overall goal in operating Stack MCP-3 was the design, fabrication, manufacture, operation, and data acquisition of an IMHEX[®] MCFC stack of full active area with sufficient cells that chemical effects, electrochemical performance, temperature profiles, and pressure drop data would be scaleable for accurate design of demonstration-size and market entry MCFC systems.

The general goal above translated into a number of individual objectives that factored into the effort to test Stack MCP-3:

- ▶ Design and manufacture full-area separator plates with the following features:
 - Reasonable pressure drop, considering the cathode gas cooling flows required in future MCFC systems.
 - Good anode flow patterns for even distribution of fuel and the capability of high fuel utilization.
 - Good dimensional tolerance for accurate stack construction.
 - Capability for good stack sealing, using the IMHEX[®] concept.
- ▶ Scale-up and fabrication of active components at the full-area size:
 - Maintaining electrochemical activity, including high catalyst activity.
 - Maintaining control of pore size distribution, porosity, thickness, and other factors inherent in the mechanical operation of the MCFC.
- ▶ Construct a multi-cell MCFC stack of about 20 kW from the components developed above.
- ▶ Operate the stack for about 1000 hrs to prove the scale-up and acquire data satisfactory for design of taller demonstration-scale stacks.

Figure 5.5-2. Individual Cell Potentials in Stack MCP-3

Comparison of First Full-Area Stack
to PSI Model

This stack employed the first-issue, MOD 1 separator plates. Because they were first-issue, all of the steps of pressing, cutting, welding, and aluminization had to be learned at the full-area size. Consequently, the separator plates were not as flat as desired, nor were the step heights and wet seal thicknesses as uniform as specified. Moreover, even the measurement techniques for determining these parameters were not considered fully satisfactory until Stack MCP-6. Plate waviness was partially corrected by welding the cathode current collector in place, and grinding the current collector within 25 - 50 mm (1-2 in) of the wet seal. Wet seal variations were compensated by paste-up with an electrolyte matrix mortar in areas where the wet seal was low. Unrolled matrices were employed for better sealing.

The conclusions of the topical report on this stack test were:

1. The M-C Power, full-area, IMHEX[®] MCFC stack design concept was verified in its first 20-kW stack test. The stack power reached 22 kW in its first attempt and that power output was only limited by the current-carrying capacity of the load dissipation device.
2. The full area components exhibited electrochemical performance at the state-of-the-art level, duplicating the cell potential achieved on the bench scale, with a scale-up factor of 100.
3. Excellent cell-to-cell performance uniformity was achieved. The standard deviation of the cell potentials was about 15 mV at 1200 A; only 11 mV when cells with end effects were discounted.
4. Material balance closures were 97% to 102%, lending credibility to the data generated.
5. The stack operated without apparent voltage deterioration for more than the test goal of 1000 hours.
6. The pressure drop across the cathode side of the stack agreed with extrapolations from the cold-flow modeling, providing confirmation of cathode recycle blower duty.
7. The ability of the stack to withstand thermal cycling was verified. The IR-free stack potential did not deteriorate from the thermal cycling.
8. The up-rated 20-kW Test Facility was functional with excellent operator control. The system operated satisfactorily for over 1000 hours, with no major malfunctions of the test hardware.

9. Operational procedures for full-area stacks were tested, modified as necessary, and verified. Preconditioning (binder removal and electrolyte melting) procedures require further attention for improved operability. Procedures to eliminate potential for soot formation should be implemented.
10. Positive mechanical results were demonstrated by the use of un-rolled matrices and a new cell package. These matrices showed good crack resistance, even after two thermal cycles. However, matrix pore structure and/or electrolyte management may require optimization, based on the relatively low performance of the stack on dilute oxidants.
11. The bipolar plates exhibited excellent uniformity, considering that they were the first-production units. With additional effort, tolerances should be improved for better ease of assembly.
12. Clamping pressure and/or fit-up should be optimized to reduce electrode extrusion into holes of the current collectors and reduce the deformation of active area components. The extruded cathode may have been a partial cause of the low performance.
13. Provisions should be developed and implemented to assure adequate stack sealing during start-up. Areas of analysis should include fit-up, clamping force, and seal rail load deflection and creep design.
14. Additional analyses and development are required to reduce the electrical resistance change of the end cells after thermal cycling.
15. Additional assessment and improvement are required to reduce the increased stack gas pressure differential after thermal cycles.

5.5.3 Stack MCP-4

M-C Power operated its second full-area, 20-kW MCFC stack, called Stack MCP-4, from November 1992 to February 1993. Stack MCP-4, with DOE funding, was the second step in the testing of the full-area stacks, building on the experience gained in the earlier Stack MCP-3. A topical report² was prepared for DOE that discussed the stack test in detail; that report should be referred to for a more complete discussion.

²Cámara, E. H., "SIMULATED COAL GAS MCFC POWER PLANT SYSTEM VERIFICATION" Topical Report for Stack Test MCP-4, December, 1995

Stack MCP-4 was rated at 20 kW and contained 20 cells with an active area of 10,570 cm² (11.37 ft²) each. Operating at atmospheric pressure, the stack delivered a maximum power output of 23 kW, and this power was only limited by the current-carrying capacity of the test facility, not the MCFC stack itself. The stack achieved state-of-the-art electrochemical performance, duplicating the cell potential that is usually achieved on the bench scale, but with a scale-up factor of 100.

The total operating time exceeded 1560 hours, including over 778 hours of operation on dilute oxidant gases similar to those expected in a full-scale, methane-fueled system with cathode recycle for stack cooling. Performance with the dilute oxidants checked the operation predicted by the PSI Model for MCFC Performance. One hot hold operation was performed without loss in performance.

The overall goal in operating Stack MCP-4 was the validation of the design, fabrication, and manufacturing techniques of full-area cells, together with the operation and data acquisition of an IMHEX[®] MCFC stack of full active area. The stack should produce about 20 kW, or contain sufficient cells that chemical effects, electrochemical performance, temperature profiles, and pressure drop data would be scaleable for accurate design of demonstration-size and market-entry MCFC systems.

The overall goal above translated into a number of individual objectives that all factor into the effort to test Stack MCP-4:

- ▶ Design and manufacture full area separator plates with the following features:
 - Increased gas manifold area, for improved cell-to-cell gas distribution on both the anode and cathode.
 - Reasonable pressure drop, considering the cathode gas flows required in MCFC systems using cathode recycle for stack cooling.
 - Good anode flow patterns for even distribution of fuel and the capability of high fuel utilization.
 - Good dimensional tolerance for accurate stack construction.
 - Capability for good stack sealing using the IMHEX[®] concept.
- ▶ Scale-up and fabrication of active components at the full-area size, maintaining:
 - Electrochemical activity, including high catalytic activity.
 - Control of pore size distribution, porosity, thickness, and other factors inherent in the operation of the MCFC.

- ▶ Construct a multi-cell MCFC stack of about 20 kW from the components developed above.
- ▶ Operate the stack, for about 1000 hrs, to prove the scale-up, acquiring data satisfactory for design of taller, demonstration-scale stacks, on the physical, chemical, electrical, thermal, and pressure effects. Data should also be acquired on dilute gases, consistent with the proposed commercialization plan.

Differences from Stack MCP-3 included the following:

- ▶ MOD 2 separator plates, with larger manifolds as required for satisfactory cell-to-cell gas distribution in taller stacks. Section 5.1.2 of this document discusses the design of this plate. Production of this plate required re-tooling of all dies, clamping fixtures, and laser welding techniques. The resulting plates were much closer to dimensional tolerances than was experienced in Stack MCP-3.
- ▶ Rolled electrolyte matrices were used in all layers, because the better separator plates did not require the unrolled matrices employed in Stack MCP-3.
- ▶ The cathode current collectors were not welded to the separator plates. This approach is time-consuming and labor intensive and must be eliminated from the stack construction procedure.

The results of the test were as follows:

1. The verification of the M-C Power, full-area, IMHEX[®] MCFC stack design concept was re-confirmed in its second, 20-kW stack test. The stack power reached 23.9 kW on diagnostic gases and that power output was only limited by the current-carrying capacity of the load dissipation device.
2. The full-size active area components exhibited electrochemical performance on diagnostic gases at the state-of-the-art level, identical with those of Stack MCP-3 and duplicating the cell potential achieved on the bench scale.
3. When operating on system gases (the oxidant gas with low concentrations of reactants as would exist in a total MCFC system with cathode recycle employed for stack cooling), the stack power exceeded the nominal design basis, reaching 21.9 kW at 1800 A (~ 170 mA/cm²).
4. The components yielded electrochemical performance on dilute oxidants that agreed with data acquired on the bench scale. The prior stack did not operate as well on dilute oxidants, indicating that the rolled matrices employed in this stack had better electrolyte management and pore-matching characteristics with the electrodes. Figure 5.5-3 illustrates the performance on system gases; the points on this graph are

Figure 5.5-3 Performance of Average Cell in Stack MCP-4

average stack data (excluding the negative cells) and the line is the prediction of the PSI MCFC model employing the mean cell IR as measured from the stack.

5. The pressure drop across the cathode side of the stack was identical with Stack MCP-3 and agreed with extrapolations from the cold-flow modeling, providing confirmation of cathode recycle blower duty. Figure 5.5-4 presents the pressure drop data. The line on this graph was derived from Stack MCP-3 data and extrapolation of the cold-flow data.
6. The positive electrochemical results were demonstrated by the use of rolled matrices and probably better electrolyte management. However, the mechanical properties of the stack were deficient, with both fuel and oxidant cross-over, cell-to-cell maldistribution of fuel, negative cells, and sensitive cells.
7. The stack operated satisfactorily, even with one or two cells producing no power and registering negative voltage. The negative cells in the MCFC system do not impact the rest of the stack; rather, the primary effect is only the reduction in total voltage output of the stack.
8. Cell 6 stopped operation early in the test; Cell 1 became negative midway through the test; and four other cells exhibited sensitivity. Both of these cells were impacted by fuel maldistribution. The cause of the maldistribution for Cell 1 was found to be carbon deposition from the feed gas. The reasons for the other cells were not determined with certainty, although the failure of Cell 6 appeared to be fuel leakage from the anode chamber directly to the cathode exhaust, causing fuel starvation.
9. The ability of the stack to withstand a "hot hold" condition was verified. The IR-free stack potential did not deteriorate from the hot hold.
10. Operational procedures for full-area stacks were tested, modified as desired, and verified. Preconditioning (binder removal and electrolyte melting) procedures require further attention for improved operability. Procedures to eliminate potential for soot formation should be implemented.
11. The new, MOD 2 bipolar plates exhibited excellent uniformity, considering that they were the first-production units of this design. Tolerances and waviness were considerably better than the plates for Stack MCP-3. With additional effort, tolerances should be improved for better ease of assembly.
12. Provisions should be developed and implemented to assure adequate stack sealing during start-up. Areas of analysis should include fit-up, clamping force, and seal rail design.

**CATHODE PRESSURE DROP
Test MCP-4**

Points Are Quarter-Hour Data Readings
Line from MCP-3 and Cold-Flow Modelling

Figure 5.5-4 Cathode Pressure Drop in Stack MCP-4

5.5.4

Stack MCP-5

M-C Power operated its third full-area, 20-kW MCFC stack, called Stack MCP-5, during June, July, and August, 1993. This test was also a 20 cell stack, using components similar to Stack MCP-4. The test was scheduled for 1,000 hours duration. Test objectives were 1) the verification of electrochemical performance on wet system gases; 2) data acquisition on alternative fuel flow, "Twin-V" configuration, discussed below; and 3) the validation of cell performance after hot hold conditions. A topical report³ was prepared for DOE that discussed the stack test in detail. That report should be referred to for a more complete discussion.

Prior stack operation had been counter-current flow of fuel and oxidant. The use of three inlet manifolds and two outlet manifolds permits alternative flow paths which might be quite advantageous, particularly in the case of the fuel flow. A "W-flow" path starts with all the fuel entering the cell in one of the small, corner manifolds. The fuel flows over one quadrant of the cell and exits that quadrant at a manifold that previously had been an exit manifold, but now is blocked off. The fuel is re-mixed in that manifold and is fed to the second quadrant of the cell. The flow by quadrants and re-mixing in the blocked manifolds continues until the spent fuel leaves the cell stack at the other small corner manifold. Compared to normal operation, the fuel flow rate, per unit area, is increased by a factor of four, as is the total path length. The increased pressure drop, together with the re-mixing stages, is anticipated to cause better cell-to-cell fuel distribution and permit higher fuel utilization.

The "W-flow" configuration was not attempted because the calculated pressure drop was excessive. Rather, a "Twin-V" flow path was tried. In this configuration, the fuel enters through both small corner manifolds and leaves from the large center manifold on the same side of the stack, after flowing across the stack and re-mixing in the blocked manifolds that had previously been exit manifolds.

Hot, motor-operated valves were installed under the stack on the test stand so that the stack could be operated either countercurrently or in "Twin-V" flow path. Unfortunately, one of the valves was manufactured incorrectly. As a result, it indicated that it was open when it was actually closed.

The closed valve caused incorrect flows in the stack during startup and binder removal was poor (as was noted during stack dismantling). The poor binder removal resulted in coking within the matrix and poor electrochemical performance.

The test did have positive aspects. For example, Stack MCP-5 was designed to be a Unocal "twin stack". Assembly of Stack MCP-5 occurred during anode and cathode manufacturing for Unocal and the electrodes were selected from Unocal inventory. Truly continuous casting of

³Cámara, E. H., "SIMULATED COAL GAS MCFC POWER PLANT SYSTEM VERIFICATION" Topical Report for Stack Test MCP-5, December, 1995

electrodes had not yet been fully developed and implemented for this effort, but was for the following stack. The separator plates for Stack MCP-5 were the initial output of a 370-plate production run, as discussed in Section 5.1.2, Design, Engineering and Manufacture of the IMHEX® Separator Plate. Plate tolerances were again improved. Both the modified grit-blasting and the longer annealing of the plate after aluminization provided better adhesion of the aluminum to the stainless steel.

The test operated for 500 hours — 400 hours on reference gases and 100 hours on wet system gases. After electrolyte impregnation and during pre-test cross-over data collection, gas measurements indicated the existence of a small outboard leak. Because of the leak, an immediate analysis of the stack axial clamping force was started, using a stack structural model recently completed. Operation on reference and wet system gases was started to establish stack baseline performance. As expected, performance was substandard. The valving error caused inefficient binder removal. After 200 hours of operation, the stack was shutdown for repairs.

Two stack modifications were made. The first was to change the stack clamping system for better control of the axial load. The stack structural analysis revealed that the seal force, at areas where outboard seals were compromised, was substantially lower with the original configuration; implementation of the new system provided an even seal pressure. The second change was the development of a method to repair outboard seals using an electrolyte matrix cement. The stack was re-started and the stack performance duplicated the earlier operation, after the thermal cycle, on reference and wet system gases. This result is important because it confirmed the resilience of an IMHEX® MCFC stack after a thermal cycle and mechanical repair. Gas analysis and stack mass balance also confirmed the integrity of the seal repair. Upon confirmation of the changes, the test was terminated. Post test inspection showed the seal repair to be sound.

5.5.5 Stack MCP-6

M-C Power operated its fourth full-area, 20-kW MCFC stack, called Stack MCP-6, from mid-November 1993 to the end of February 1994. That stack test was quite successful, meeting all of the test plan goals, and generating data for the design of the 250-cell Unocal stack. The objectives of the test were 1) to validate a new cell assembly approach; 2) to confirm cell performance using wet system gases; 3) to validate the hot hold conditions; and 4) to confirm the axial sealing efficacy of the new clamping system. A topical report⁴ was prepared for DOE that discussed the stack test in detail. That report should be referred to for a more complete discussion.

Stack MCP-6 was rated at 20 kW and contained 20 cells with an active area of 10,570 cm² (11.37 ft²) each. Operating at atmospheric pressure, the stack delivered a maximum power output of 23 kW, and this power was only limited by the current-carrying capacity of the test facility, not the MCFC stack itself. The stack achieved state-of-the-art electrochemical performance, duplicating

⁴Cámara, E. H., "SIMULATED COAL GAS MCFC POWER PLANT SYSTEM VERIFICATION" Topical Report for Stack Test MCP-6, January 1996

the cell potential that is usually achieved on the bench scale, but with a scale-up factor of 100. Figure 5.5-5 presents polarization data for the average cell in the three successful full-area stacks. At a current of 1600 A ($\sim 150 \text{ mA/cm}^2$), the variation in the average cells is only about 20 mV, and this was caused by the slightly higher internal resistance of Stack MCP-6. Also included on this graph is the prediction of the PSI MCFC performance model. Stacks MCP-3 and -4 follow the model closely, and Stack MCP-6 operated better than expected.

The components were similar to those in the earlier stacks, except that they were manufactured by continuous processes. A change from the earlier stacks was the use of un-rolled matrices. Proof of the performance of these matrices had been achieved on the bench scale, so the change was implemented.

Prior to stack assembly, extensive testing was conducted, using pressure sensitive paper, to qualitatively evaluate the new cell assembly approach. In the new approach, the cell is assembled with the active components set at a small, predetermined distance below the seal plane. All prior stacks had been fitted with the active components above the seal plane. Therefore, unless good force distribution is obtained, poor electrical contact is possible. Good sealing was obtained, and the active area force distribution was adequate.

A total of 1071 hours of operation was logged — 533 hours on reference gases and 538 hours on wet system gases. The maximum power output was 23 kW on reference gases and 21 kW on wet system gases. Performance data were collected on reference and system gases for fuel utilizations ranging from 60-75%. Baseline crossover and stack mass balances indicated that good outboard seal efficiency was achieved with the new assembly approach. An issue that required validation during stack operation was that, in fact, cell internal resistances were not compromised.

As mentioned above, all active components — anodes, cathodes, and electrolyte matrix — were made by continuous manufacturing processes. In fact, the parts were taken from the same general inventory as the Unocal stack. Thus, M-C Power has been able to achieve true continuous manufacturing of MCFC components without loss in stack performance. In fact, the voltages are identical to the electrochemical model predictions and well-controlled bench-scale tests.

One negative aspect of Stack MCP-6 was the cathode-side pressure drop. In this test, that pressure drop was similar to other tests at the start of the test, but unlike the other tests, pressure continued to climb during the test. After stack dismantling, it was found that the feed-rails had overly compressed. This compression was probably caused by the negative fit-up, discussed above. For the stack to be electrochemically active with negative fit-up, the wet seal rails must compress about 0.1 mm (4 mil). Apparently they continued to compress during the test. A separator plate from Stack MCP-4 was re-examined, and the feed rails were found to have taken a permanent set. This phenomenon is called load relaxation and is related to creep and stress relief as a strength-at-temperature, with time, effect.

Figure 5.5-5 Comparison of the Average Cell in Three Full-Area Tests

Consequently, the feed system for the separator plates was re-engineered into the MOD 3a plate discussed in Section 5.1.2, Design, Engineering, and Manufacture of the IMHEX® Separator Plate.

5.5.6 Inputs To Unocal 250-Cell Stack

As discussed above, the 250-cell Unocal stack was to have been made of components identical to Stack MCP-6. Its performance, therefore, should be identical, per cell. One major difference was the change to the MOD 3a separator plate design. This necessitated changing the separator plates that had already been made. The feed rails were removed and the modified feed system was installed. Another change was also required. The shape of the electrodes and current collectors were modified, because they covered the feed inlet opening. This necessitated re-casting and re-sintering the electrodes so that they could be cut to the new planform.

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5.6 Subtask 5.6 Performance Issues

Objective:

To design and develop an effective technique to prevent anode-to-cathode gas crossover through the matrix.

To develop and evaluate novel electrolyte replenishment techniques in out-of-cell tests and to investigate approaches for increasing the electrical conductivity of oxide layers on the separator plate by reducing growth rate and by doping in out-of-cell tests. To upgrade the performance/endurance model to include improved kinetic algorithms and to develop a failure mode analysis and a cell/stack component characteristic and performance data base to be incorporated into the model to improve its functionality.

Discussion:

During the period of the contract, the original goals of this project task were modified, as impacted by the progress (and/or cost) of individual effort. The subtasks on electrolyte replenishment and separator plate conductivity were de-emphasized and the comprehensive stack model, including failure mode analysis, was scaled back. Rather, the desired effort was undertaken as summarized below.

5.6.1 Eliminate Gas Leakage Within Cell

Objective:

To design and develop an effective technique to prevent anode-to-cathode gas crossover through the matrix.

Summary:

Under this subtask, effort was concentrated on developing an alternate cell concept wherein the cathode is extended to the outer edge of the wet seal. Work was performed to develop electrode porosity fillers necessary to decrease and/or eliminate the possible gas leakage and cell conformity problems encountered when extending the electrodes to the wet seal area. The purpose of the electrode porosity filler is to fill the exposed peripheral edges of electrodes and protect them from deleterious chemical and physical changes during cell operation. With the Ni cathode, the best results were obtained with Mg-Al under an atmosphere of He at 550°C (1022°F) and with Mg under an atmosphere of He at 750°C (1382°F). With the Ni+10% Cr anode, good results were also obtained with Al-foil under an atmosphere of He at a temperature of 1100°C (2010°F) and with Al-foil glued to the sample with Ni slurry (as used for tape casting) under the same conditions. Based on these results, Al alloys with melting points as low as 450°C (840°F) show a good potential for electrode edge modifications.

An out-of-cell test rig was designed and fabricated to determine the severity of the perceived interaction between the electrodes exposed to various gas atmospheres. The purpose of this test rig was to simulate the gas compositions and pressures which can be encountered at the edges of porous electrodes extended into the wet seal area.

Three preliminary shakedown tests were conducted in this out-of-cell test rig. The purpose of the first test was to establish the baseline sealing characteristics of the unit and of a standard carbonate-filled LiAlO_2 matrix. The test operated for over 1500 hours at a temperature of 650°C (1200°F) and a clamping force of 15 psi (103 kPa). Results revealed no gas crossover from cathode to anode at pressures up to 30 inches (76 cm) w.c. The second test was assembled with the standard electrolyte matrix specimen and operated for 2340 hours at a temperature of 650°C (1200°F) using the standard gas compositions ($75\text{H}_2/25\text{CO}_2$ fuel and $70\text{Air}/30\text{CO}_2$ oxidant). The purpose of the test was to shakedown a new clamping and alignment fixture.

One hour after reaching the operating temperature of 650°C (1200°F), a large unmeasured load (>50 psi or 344 kPa) was placed on the specimen. Shortly thereafter, the clamping force for the rest of the test duration was adjusted to 28 psi (193 kPa). The test results indicated no gas crossover between the matrix cathode side and anode side for pressures up to 30 inches (76 cm) w.c. Disassembly of the rig revealed that extrusion of the matrix out of the sealed area had taken place (attributed to the large transient clamping force of 50 psi or 344 kPa). The third test was a repeat of Test No. 2 and operated for 50 hours at 650°C (1200°F) with larger cathode pressures of up to 100 inches (254 cm) w.c. instead of 30 inches (76 cm) w.c. used in the earlier two tests. The primary purpose of repeating Test No. 2 was to see if extrusion of the matrix had taken place between two stainless steel non-compliant plates with a clamping force of 28 psi (193 kPa) and a wet seal width of 0.5 inch (12.5 mm) instead of 0.28 inch (7.1 mm). Post-test examination revealed no significant extrusion of the matrix.

Three bench scale tests were also conducted with the cathode extended to the cell periphery. Bench-scale test IGT-BS-TC-61-91-2 was operated using a cathode extended to the edge of the wet seal. The purpose of this test was to determine if better thermal cycling and gas sealing could be obtained by providing a uniform support of the matrix over the traditional wet seal/active area transitional line where the matrix could crack and/or fracture if a gap exists between the current collector and the wet seal area. The cell operated for 1493 hours and the initial cell potential varied from 725 mV to 730 mV at $160\text{ mA}/\text{cm}^2$ ($149\text{ A}/\text{ft}^2$) with an OCV of 1040 mV. The cell potential at termination was 728 mV at $160\text{ mA}/\text{cm}^2$ ($149\text{ A}/\text{ft}^2$). Cell IGT-BS-TC-61-91-2 successfully demonstrated the concept of the cathode extended to the wet seal edge.

The second cell, IGT-BS-TC-72-92-2, was operated for the purpose of assessing the feasibility of extending both the cathode and cathode current collector to the wet seal edge, but with only a 0.001 inch (0.025 mm) layer of Al foil on the cathode wet seal and no metallurgical joint at the cathode current collector wet seal interface. This cell has provided significant information regarding the criticality of uniform support across the entire matrix area. This cell operated for 4368 hours and the performance at $160\text{ mA}/\text{cm}^2$ ($149\text{ A}/\text{ft}^2$) remained high and stable at 773 mV with an

OCV of 1045 mV. The cell was thermal cycled twice. This cell test demonstrated the high performance achievable when there are no discontinuities of elevation or hardness in the mechanical support over the entire matrix area.

The third cell, IGT-BS-TC-72-92-4, was a repeat of Cell IGT-BS-TC-72-92-2 with its cathode and cathode current collector extended to the edge. Cell IGT-BS-TC-72-92-4 was terminated at 2474 hours after a power outage occurred at 2277 hours and after every attempt was made to restore its performance. Prior to the power outage, the cell potential at a current density of 160 mA/cm² (149 A/ft²) was 715 mV but had decayed to 649 mV at termination. The loss in performance was caused by an increase in IR and N₂ crossover. This test did not confirm the good performance of cell IGT-BS-TC-72-92-2.

5.6.2. Decrease Long Term Voltage Decay in Stacks

Objective:

The objective of this subtask was to evaluate electrolyte loss mechanisms that contribute to performance decay and to develop means of eliminating or offsetting the effects of the most significant.

Summary:

One of the chief causes of long term performance decay in MCFC stacks is the loss of electrolyte. Three electrolyte loss mechanisms have been identified. These are electrolyte vaporization, liquid film creep, and chemical reaction with cell hardware. Electrolyte vaporization losses were measured directly in a bench-scale cell operating under system conditions. These losses were projected to be well within acceptable limits for up to 40,000 hours of operation. Losses due to liquid film creep are significant for small lab-scale single cells and moderate for bench-scale cells. However, since electrolyte loss occurs primarily at the outer perimeter of the wet seal, the impact of liquid film creep on cell or stack performance should be highest for lab-scale cells and low for full-area commercial-scale stacks with a high volume to perimeter ratio. Electrolyte losses due to chemical reaction with the cell hardware were not addressed under this task.

5.6.3. Develop a Comprehensive Stack Performance Model

Objective:

The objective of this subtask was to develop a comprehensive stack performance model that could be used both as an element in a systems model to optimize the balance-of-plant and as a stand alone model to optimize stack components.

Summary:

The Physical Sciences Incorporated (PSI) MCFC Performance Model was adapted to run on an IBM-compatible personal computer and was validated against the performance of the M-C Power 70-cell sub-scale stack. Model predictions of performance for the central cells of the stack deviated from actual measured values by less than 1%. The model-predicted temperature for the center of the stack deviated from the actual measured value by only 8°C (46°F). A new cathode model also was written and incorporated into the PSI model. The new cathode model uses more realistic input parameters than the original model and can be used to predict optimum cathode thickness, pore filling, and pore size distribution for a given set of system operating conditions.

5.6.4 Short-Term Subscale Stack Testing

Objective:

The original objective of this subtask was to fabricate, assemble, and operate two subscale 1,000 cm² (1 ft²) stacks for up to 1000 hours each to verify the advanced components and procedures developed under Subtasks 5.4 and 5.6. However, before any subscale stacks were operated and at the direction of M-C Power, IGT was redirected to concentrate efforts on materials/component development and verification in bench-scale tests leading to higher performance and higher endurance.

A shift in work emphasis was also initiated early in the contract period to reflect the elimination of one of the subscale stack tests and replace this work with the completion of the construction and shakedown of a 1,000 cm² (1 ft²), 2-kW stack test facility at IGT.

Summary:

Also, at the request of M-C Power, all of IGT's efforts were directed to materials/components development and verification in bench-scale tests. In view of these changes, activities leading to Stack IGT-7, and any other future stacks were suspended.

5.6.4.1 Increase Cathode Performance

Objective:

The goal of this subtask was to optimize the cathode pore structure following suggestions derived from the new cathode model. An increase in output voltage of 30 to 35 mV was anticipated.

Summary:

According to the PSI PC-based performance model (Subtask 5.6.3), the typical cell performance at the system condition of 200 mA/cm² at 3 atm (303 kPaa) with system fuel at 75% utilization and system oxidant at 40% utilization is 716 mV. This has been verified by running a fuel

cell at the specified conditions with a cell package consisting of a 15-mil (0.37mm) Gould cathode, a 30-mil (0.75mm) Gould Ni+10Cr anode, an IGT reinforced matrix, and 70Li/30K electrolyte whose loading was for 100% filling of the matrix pores and 25% filling of electrode pores.

On the other hand, at the start of this subtask, the IGT 1992 baseline cell package consisting of a 30-mil (0.75 mm) low-density Ni cathode and a 30-mil (0.75 mm) Ni+5Cr anode, a reinforced matrix, and 70Li/30K electrolyte whose loading was for 100% filling of the matrix pores and 40% filling of electrode pores produced just 666 mV at the specified cell operating conditions.

The major factors that could explain the difference in their performance behavior are a thicker cathode (30 mils vs 15 mils or 0.75 mm vs 0.37 mm) and a higher carbonate loading (40% vs 25% target electrode fills) for the IGT baseline cell. The thicker cathode is desired for a higher Ni loading while the higher carbonate loading is for cell endurance.

From the breakdown of cell performance parameters, it can be seen that, for further improvement in cell performance, cathode polarization and/or ohmic resistance have to be reduced. Since the performance of the baseline IGT cell had not matched the predicted performance, efforts were made to improve the cathode to at least match the predicted cell performance so that assessments can be made for further improvements.

Therefore, efforts were made to optimize the cathode pore structure without having to significantly change the cathode raw materials, processing scheme, thickness, and the high carbonate loading for the IGT baseline cell. From particle packing studies, it appears that at 40% carbonate loading, the baseline cathode with 80% porosity is likely to have a thick layer of electrolyte film that would hinder gas diffusion. A higher Ni loading will not only increase the active surface area but will also distribute the electrolyte to a thinner layer for more efficient gas diffusion. Thus, the Ni loading of the cathode was increased from about 20 vol%(80% porosity) to nearly 30% (70% porosity). Two cells with this modified cathode have improved performances over the 1992 baseline cells and have closely matched the performance of the Gould electrodes.

In addition to improving the baseline Ni cathode pore structure, attempts were also made to increase the cathode pore size for improved gas transport by adding pore formers and various Ni additives. However, improvements made were not tested in fuel cells because of project time limitation.

5.6.4.2 Increase Electrolyte Conductivity

Objective:

The objective of this task is to determine if cell performance can be increased by a substitution of a higher conductivity Li/Na electrolyte or Li/Na/K electrolyte for the state-of-the-art Li/K electrolyte.

Summary:

The Li/Na electrolyte offers higher ionic conductivity, higher exchange current density, lower vapor pressure, and lower solubility to the NiO cathode than the conventional Li/K electrolyte. The Li/K electrolyte has been favored historically because of its low melting point and its broad range of liquid stability. Concerns with the Li/Na electrolyte include a narrow range of melt stability, poor wettability, and severe corrosion rate.

Under this subtask, the Li/Na electrolyte was tested in bench scale cells as an alternative to Li/K and to reduce cell resistance. The composition of 60 Li/40 Na was formulated. Its Li content is higher than the eutectic 52Li/38Na to ensure that the steady state electrolyte composition, after all lithiation reactions have taken place, is close to the eutectic 52Li/48Na. Two 100-cm² (0.1 ft²) cells were operated with this electrolyte using a Ni+5Cr anode and a Ni cathode. These cells had low IR as a result of the low ionic conductivity of the Li/Na electrolyte. However, their polarizations were high. Upon post test analyses, it was determined that the cathode was poorly wetted by the Li/Na. A less wetting Ni+3Cr anode was therefore used in the subsequent cells and it was matched with a stabilized Ni cathode for reduced cathode dissolution. This second set of cells not only have low IRs but also low polarizations. The cell performance at 1 atm reached 805 mV at 160 mA/cm² (149 A/ft²) with reference gases at 75% fuel utilization and 50% oxidant utilization. The decay rate was 2 mV/1000 hours. The cell performance at 3 atm (303 kPaa) reached 770 mV at a current density of 160 mA/cm² (149 A/ft²) with system gases at 75% fuel utilization and 40% oxidant utilization. The decay rate was 4 mV/1000 hours.

In-cell cathode dissolution data were obtained from cells operated with Li/Na electrolyte. Results are very encouraging in that the dissolution is greatly reduced. The rate of Ni transported to the matrix is also slow. These results are discussed under Subtask 5.7.2.

5.7 Subtask 5.7 Endurance Issues

Objective:

To improve component longevity by continued development of creep-resistant anodes and cathodes, to determine the effectiveness of the strengthening mechanisms in out-of-cell tests and in bench-scale single cells, and to verify success in a stack test.

To evaluate the efficacy of doping for reduction of the cathode dissolution rate and to develop a tape casting process for continuous fabrication of stabilized cathodes.

Discussion:

5.7.1 Improved Longevity of Components

Objective:

The objective of this subtask was to develop a low cost creep resistant anode that would require little or no reinforcement when used without a current collector. Present available Ni+Cr anodes can not be used without a current collector and are therefore being strengthened by such techniques as screen reinforcement, increased thickness, densification, or a combination of these approaches. If a sufficiently strong anode can be developed, it may not require reinforcement. IGT's goal was to develop anodes having a maximum creep rate of 1% with a porosity of greater than 50%. Efforts under this subtask focused on developing a cost effective Ni-Al anode.

Summary:

IGT's effort under this Subtask was reported separately to M-C Power; this discussion summarizes that report¹. Process development work on Ni-Al anodes resulted in significant simplification of the process for making oxide dispersion strengthened (ODS) anodes. A Ni+Al anode having a 50% porosity showed a creep of 0.77% at 650°C (1200° F) under a 100 psi (690 kPa) load. These anodes were prepared by a one step sintering/oxidizing process. Alternatively, a Ni+Al+NiO anode was prepared similarly. It showed a creep of 0.3-0.6% under the same loading conditions as the Ni+Al anodes. In bench cell tests, the Ni+Al anode performed well, reaching 746 mV at 160 mA/cm² (149 A/ft²). However, for reasons not understood, the electrolyte in the anode had an extremely high Li/K ratio whose composition forms solid Li₂CO₃ at 650°C (1200° F). The cell test with the Ni+Al+NiO anode was, however, inconclusive because of a defective cathode current collector. This process appears to be the most cost effective for Ni-Al anodes and is recommended for continued development. However, additional testing of Ni-Al anodes is recommended to determine their performance and stability behavior to justify the replacement of Ni+5Cr anodes. For example, it was found that the Li/K ratio of the carbonate in the anode is a

¹Marianowski, L. G., "SIMULATED COAL GAS MCFC POWER PLANT SYSTEM VERIFICATION" Subcontract Report December, 1955

concern since it indicates that the carbonate phase is solid. More tests are needed to understand this observation. Also, no tests using the Li/Na electrolyte have been made, and tests using this mixture are essential since it has shown several advantages over the traditional Li/K. Another good reason for testing Li/Na with Ni-Al is the poor wetting of Li/Na on the cathode. Since the Ni-Al is also poorly wetted, it may be a better anode for the Li/Na than the presently used Ni-3Cr in terms of both pore matching and strength.

Improvements were also made with Ni+Cr anodes. The traditional Ni+10Cr anode composition has been reduced to Ni+5Cr without sacrificing creep resistance. A Ni+3Cr anode composition can also be prepared but at a lower porosity than the Ni+5Cr anode to possess comparable creep and carbonate retention properties. The lower Cr content of the anode means less Li_2CO_3 to be consumed for anode lithiation, and hence, easier carbonate management for the cell package. The reduction of anode Cr content became possible by the use of fine Cr powder.

5.7.2 Cathode Life Extension — Cathode Dissolution

Objective:

To evaluate the efficacy of doping NiO cathode for reduction of the cathode dissolution rate and to develop a tape casting process for continuous fabrication of the doped cathode.

Summary:

A dopant is being added to the cathode to reduce cathode dissolution. IGT has developed two types of stabilized Ni cathodes.

One of the stabilized cathode types performed better than the others. The reason was not initially understood, partly because the cells were operated in new test facilities, which suffered several upsets during the stabilized cathode tests. Subsequent data, after the end of this program, revealed microstructural characteristics as the reason for the different performance. Adjustments have been made so that both types of stabilized cathodes now perform equally well.

During the subtask duration, cathode dissolution data from cells with electrolyte compositions of 62Li/38K, 70Li/30K, 70Li/30K with stabilized Ni cathode, and 60Li/40Na were generated. Results are consistent with the acidic dissolution mechanism in that cathode solubility is lower in the more basic electrolyte. Therefore, the order of decreasing cathode dissolution is-

$$62\text{Li}/38\text{K} > 70\text{Li}/30\text{K} > 70\text{Li}/30\text{K} + \text{stabilized cathode} > 60\text{Li}/40\text{Na} \text{ (least)}$$

Moreover, results with Li/Na electrolyte are so far encouraging because, not only does the Li/Na show the least dissolution, the build up of Ni precipitates in the matrix is also very slow. More in-cell data are needed to verify this result.

5.7.3 Mid-Term Subscale Stack Testing

During this contract period, IGT operated Stack IGT-6 under funding from SDG&E as cost-sharing into the overall DOE program. A separate topical report² was issued on that effort. This report summarizes the testing of a subscale, 1 ft² (1000 cm²) 20-cell IMHEX[®] molten carbonate fuel cell (MCFC) stack, Stack IGT-6 (SDG&E-1), which was sponsored by SDG&E. This stack was fabricated and assembled at IGT and operated for 7163 hours at IGT's stack testing facility. This endurance testing was conducted in support of M-C Power's commercialization plan.

The original purpose of Stack IGT-6 was to scale up and demonstrate the long-term performance and endurance characteristics of the IMHEX[®] stack design and cell components in a 4000 hr, 20-cell, subscale stack test. All of the anodes and reinforced matrices were taped on M-C Power's full-area tape caster. This stack test also included the first scale-up and validation of an IGT-developed, cost-effective binder system for the components, the matrices, and carbonate tapes. IGT also developed and implemented a fast-drying electrode slurry formulation on the full area tape caster, which facilitated true, continuous tape casting.

Stack IGT-6 began operation in early February, 1992. In early August, this stack attained the goal of 4000 load hours of operation. Because of its good and steady performance, the sponsors decided to continue the test. In all, Stack IGT-6 operated a total of 7163 hours and exceeded the original objective by about 80%.

To simulate the actual operation of a power plant, Stack IGT-6 was operated at a constant load (interrupted only every $\approx$ 1000 hours for diagnostic purposes) of 160 mA/cm² (149 A/ft²) with a 38% fuel utilization for over 6000 hours. During this period, it produced over 12 MW-hours of power at an average of 2.3 kW. The steady state current was maintained with reference gases: 75 H₂/25 CO₂ fuel and 70 Air/30 CO₂ oxidant set for a utilization of 14% to 17%, consistent with maintaining an average cell temperature of 650°C (1200°F).

5.7.4 Alternative Cell Concept

Objective:

The objective of developing an alternative cell concept is to revolutionize the way the molten carbonate fuel cell is assembled to ease the component handling and assembly, and thereby minimize component damage and overall fuel cell cost. The effort was focused on laminating the components by successive tape casting thus reducing the number of component pieces handled.

Summary:

A laminating technique was developed for electrode/matrix/carbonate composite laminate. A pair of cathode/matrix/carbonate and anode/matrix laminates were tested in a 100-cm² (0.1 ft²)

²Petri, R. J., "MCFC SUBSCALE STACK ENDURANCE TESTING" Topical Report for Stack IGT-6, January, 1994

bench scale fuel cells. Both laminates were extended to the edge of the cell. To protect the anode edge from oxidizing, a frame of LiAlO_2 tape was applied around the anode which was not very effective in preventing anode gas from leaking. As a result, the cell OCV was low and the performance was poor. Sealing may be improved if the LiAlO_2 frame were reinforced or replaced by a more effective means of anode sealing. The work on developing such types of sealing is discussed in Section 5.6.1.

6. TASK 6. ADVANCED RESEARCH AND TECHNOLOGY DEVELOPMENT

The objective of this task was to address technology issues generic to MCFCs under Advanced Research and Technology Division (AR&TD) funding.

6.1 Subtask 6.1 Reduced Contact Resistance at Cathode Separator Plate Interface

Objective:

To quantitatively assess contact resistance at the interface between the cathode, the cathode current collector, and the cathode side of the separator plate and to identify and evaluate approaches to reducing and stabilizing this resistance.

Discussion:

This effort was subcontracted to IGT. This program task was directed toward lowering the contact resistance at the cathode/current collector and the current collector/separator plate interfaces in molten carbonate fuel cells where 316L stainless steel is used to fabricate the cathode current collector. The results of this study indicate that it is possible to place an electrically conducting layer between these components that both improves conductivity and reduces the rate of corrosion of the stainless steel used to fabricate the current collector and the separator plate. Two materials were investigated for forming this layer, iron (III) oxide and iron metal. If metallic iron is applied, it forms iron oxide when the MCFC is heated to operating temperature. This iron oxide layer grows in the cathode environment at a very slow rate forming a bond between components. Likewise, the same result can be achieved by applying a thin film of iron oxide to the stainless steel. Further improvement in conductivity comes as a result of the iron oxide layer growing into the porous nickel oxide cathode forming a strong, electrically conducting bond with the nickel oxide. In addition to improving the conductivity, the iron oxide layer also protects the underlying stainless steel, adding to the life span of the material and significantly slowing the leaching of chromium from the metal into the electrolyte.

The largest cell tested under this program was a 3 cm² (0.46 in²) lab-scale cell and 316L was the only stainless steel evaluated. The next step, which is left for future programs, is to scale up the experiments to 100 cm² (15.5 in²) bench-scale and 1,000 cm² (155 in²) sub-scale cells operating under MCFC power plant conditions.

6.2 Subtask 6.2 Advanced MCFC Component Research

Objective:

To conduct research to resolve issues relating to the improvement of the efficiency and cost effectiveness of the MCFC by improving the following: protection of the current collector plate from corrosion; reduction of cathode overpotential losses; understanding the effects of electrolyte basicity

and oxygen reduction kinetics to reduce cathode overpotential; and measuring the wetting angles of various electrolytes to reduce the electrolyte loss/migration during the MCFC operation.

Discussion:

This task of the AR&TD project was directed at obtaining basic data of value to all MCFC developers. The work on this subtask was subcontracted to three different university laboratories, as indicated below:

- ▶ University of Minnesota (Uminn) subcontracted for work on Hot Corrosion of Separator Plate Structure (Subtask 6.2.1).
- ▶ Texas A & M University subcontracted for work on Oxygen Electrode Studies in Carbonate Melts (Subtask 6.2.2).
- ▶ Illinois Institute of Technology subcontracted for work on Investigation of Wetting Angle Phenomena Related to MCFC Performance (Subtask 6.2.3).

The effort was originally anticipated to be a 3-year program. However, due to funding limitations, DOE terminated the effort after the first year. Final reports from each of the subcontractors have been assembled into a separate final report for DOE's AR&TD. A summary of each University's effort is given below.

6.2.1 Hot Corrosion of Separator Plate Structures

Objective:

To evaluate the concept of "windows" for a corrosion resistant current collector-separator plate for a molten carbonate fuel cell.

Summary:

Two main experimental thrusts of this subtask were (a) the preparation of Al-coated test coupons by pack-cementation and (b) the evaluation of hot corrosion reactions in a controlled "window" (described below) environment.

During the first year of the program, UMinn emphasized the preparation of Al-coated coupons for hot corrosion testing. This effort included setting up a laboratory-scale pack-cementation furnace, making coatings, and evaluating those coatings. This project completed its first year effort by evaluating the concept of "windows" as a key part of a corrosion resistant current collector-separator plate for a molten carbonate fuel cell. Equipment was procured, preliminary coating runs using the pack-cementation process were conducted and preliminary evaluation procedures to corrosion-test the "window" structure were developed. The principal goal of the project was not achieved because DOE terminated the program after the first year.

6.2.2 Oxygen Electrode Studies in Carbonate Melts

Objectives:

- ▶ Develop a microelectrode technique for determination of mass transport parameters of oxygen species (peroxide, superoxide) and of electrode kinetic parameters in bulk melt.
- ▶ Use microelectrode technique to determine the effects of electrolyte cations in the melts alternative to the standard range of $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$ eutectics or in off-eutectics on oxygen reduction kinetics.
- ▶ Investigate electrode kinetics of a micro-meniscus electrode/electrolyte interface and its applicability to porous electrodes.
- ▶ Investigate oxygen reduction kinetics on selected oxide alternatives to nickel oxide as oxygen cathodes.
- ▶ Develop a computer-modeling of the experimental data.

Summary:

Although there have been several previous studies to determine electrode kinetic and mass transport parameters on gold electrodes (foils, rotating discs) using cyclic voltammetric, pseudo-steady state, and impedance techniques, it has been possible only to obtain information on the product $D^{1/2}C$ (where D is diffusion coefficient and C is concentration) of the oxygen species in the carbonate melts. The unique aspect of the work under this task is that it was designed to yield the individual values of D and C .

During the first year of this project, Texas A&M focused their efforts on the first task. A literature search was conducted to review the status of the oxygen reduction kinetics in the molten carbonate electrolytes. The literature shows that mass transport overpotential plays a vital role in oxygen reduction kinetics and thus it is essential to gain information on the solubilities and diffusion coefficients of these species. The only method which has proved to be valuable for determining these parameters for oxygen reduction in other fuel cell electrolytes is the microelectrode technique.

Three designs of gold microelectrodes, using alumina tubes and seals, were considered. One of these (microwire microelectrodes) was pursued for the experimental studies. The cyclic voltammogram on such a microelectrode in sulfuric acid at low temperatures ($< 100^\circ\text{C}$ or $< 212^\circ\text{F}$) confirmed that there were no leaks in the gold alumina seals. Using a 62% Li_2CO_3 , 38% K_2CO_3 electrolyte at 700°C (1290°F), the cyclic voltammograms, recorded at several sweep rates between 50 and 250 mV/s, revealed the superoxide ion as the primary oxygenated species. By an analysis of the current versus $t^{-1/2}$ (where t is the time plot), after perturbing the potential from the open circuit value (E_o) to -0.6V versus E_o , the diffusion coefficient and solubility of the oxygen species

were calculated to be $1.5 \times 10^{-6} \text{ cm}^2 \text{ s}^{-1}$ ($1.6 \times 10^{-9} \text{ ft}^2 \text{ s}^{-1}$) and $7 \times 10^{-8} \text{ mol cm}^{-3}$ ($2.4 \times 10^{-12} \text{ mol ft}^{-3}$), respectively. The successful development of the microelectrode technique for investigations of oxygen reduction kinetics in molten carbonates could lead to the overall objectives, proposed for the three year project. However, as stated earlier, DOE decided to discontinue the program after the first year because of funding limitations.

6.2.3 Investigation of Wetting Angle Phenomena Related to MCFC Performance

Objective:

To clarify the phenomena occurring in the 3-phase boundary region of solid electrode, reactant gas, and liquid molten carbonate under cathode operating conditions.

Summary:

This research consisted of two studies. One of these was the formation of a meniscus at a gold electrode partially immersed in molten carbonate, in order to determine the reaction zone. Another was the observation of surface changes on a nickel electrode during *in-situ* oxidation and lithiation, in order to clarify electrolyte behavior during those processes. Furthermore, the basic electrochemical performance of an *in-situ* lithiated NiO electrode was compared with that of an inert (gold) electrode.

The system used for the experiments had four main parts: an electric furnace containing a test cell; electrochemical measurement equipment; optical observation equipment; and a gas supply unit. The test cell and electrodes were located in the middle of the furnace. The following electrodes and electrolyte were used:

- ▶ Working electrode (WE) : Gold foil of $25 \times 25 \times 0.1 \text{ mm}$ ($1 \times 1 \times 0.004 \text{ in}$) with gold wire of $\phi 1 \text{ mm}$ (0.04 in)
: Nickel foil of $25 \times 25 \times 0.25 \text{ mm}$ ($1 \times 1 \times 0.01 \text{ in}$) with gold wire of $\phi 1 \text{ mm}$ (0.04 in)
- ▶ Reference electrode (RE) : Partially coiled gold wire of $\phi 0.5 \text{ mm}$ (0.02 in)
- ▶ Counter electrode (CE) : Ringed gold wire of $\phi 1 \text{ mm}$ (0.04 in)
- ▶ Electrolyte : Eutectic carbonate $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3=62/38 \text{ mole } \%$

The study revealed several remarkable and unexpected aspects of the system studied. First, intense gas evolution was found to occur during Stage II (main plateau). Second, during Stage I (and presumably later as well) fine particles were seen to spall from the foil and to be convected away from it, down the meniscus. It is not clear if these particles were of nickel metal or nickel oxide, but in any case, the oxidation process apparently creates intense local stresses at the oxidation front. The third surprising observation was that this particle motion took place at relatively high apparent speed (estimated at several mm/s). This indicated that the electrolyte underwent intense convection during the oxidation process. Such convections may be caused by heat effects or by surface energy gradients (Marangoni effect, interfacial turbulence), or both.

These observations are relevant for an understanding of the *in-situ* oxidation process to which nickel is usually subjected in MCFC stacks. In particular, the role of heat effects (which are known to be considerable during *in-situ* nickel oxidation) and the exact extent of electrolyte loss associated with the oxidation process, is of interest.

The results of this study show that:

1. The contact angle on an inert (gold) electrode was almost 60 degrees, determined by observation of the meniscus height. There appeared to be no thin film formation above the meniscus.
2. Electrolyte movement from the meniscus to the non-immersed part of the nickel electrode was observed in the initial stage, followed by a hot corrosion reaction at this part of the electrode. The hot corrosion reaction is possible because the nickel electrode is wettable under cathode conditions in the MCFC. Although the reactions take place, and involve gas, solid and liquid phases, the detailed mechanism could not be clarified in this experiment.
3. A cross section of the immersed part of the Ni electrode, after steady-state had been reached, seemed to have five layers. The central layer seemed to be Ni metal. The middle and outer layers were green and black, respectively. The surface of the green colored layer seemed more smooth than the black colored layer.
4. The polarization characteristic of the *in-situ* lithiated NiO electrode shows an almost linear relationship between the current and the applied potential. The influence of the depth of immersion on these characteristics are recognizable at high applied potential. Under applied potential the current shows the tendency to increase with immersion. However, under an applied potential of less than 300 mV, depth of immersion makes no difference.