Molten Carbonate Fuel Cell Product Design & Improvement - 1st Quarter, 1996

**Quarterly Report
January 1 - March 30, 1996**

Work Performed Under Contract No.: DE-FC21-95MC30133

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

By
M-C Power Corporation
8040 South Madison Street
Burr Ridge, Illinois 60521

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

TABLE OF CONTENTS

<u>Item</u>	<u>Page</u>
COVER PAGE	1
TABLE OF CONTENTS	2
LIST OF FIGURES	5
STATEMENT OF COOPERATIVE AGREEMENT OBJECTIVES	6
SUMMARY OF WORK ACCOMPLISHED DURING THE REPORTING PERIOD BY TASK ..	7
TASK 1: PRODUCT DEFINITION AND PLANNING	7
Subtask 1.1: Identify Requirements	7
Analyze Market Surveys, Codes and Regulations	7
Subtask 1.2: Generate Product Definitions	7
Product Marketing Efforts	7
Subtask 1.3: Product Goals	7
Subtask 1.4: Commercialization Plans (Including NEPA)	7
Subtask 1.5: Task Management and Reporting	8
TASK 2: SYSTEM DESIGN AND ANALYSIS	8
Subtask 2.1: Power Plant System Optimization	8
Subtask 2.2: Generate Preliminary Design	8
Power Plant Process Design	8
Power Plant System Engineering	8
Subtask 2.3: Detailed Cost Estimate	9
Subtask 2.4: Performance Analysis	9
Power Plant Dynamic Simulations	9
TASK 3: MANUFACTURING PROCESS DEVELOPMENT	9
Subtask 3.1: Cell Component Manufacturing Process Simulation	9
Computerized Cell Component Manufacturing Process Simulation	9
Automate Current Cell Component Manufacturing	9
Subtask 3.2: Cell/Stack Hardware Manufacturing	10
Subtask 3.3: Develop Advanced Manufacturing Processes (Cell/Stack Components)	10
Develop Advanced Manufacturing Processes	10
Subtask 3.4: Manufacturing Process Scale-Up	10
Subtask 3.5: Cost Reduction	10
Lower Cost Stabilized Cathode	11
Stabilized Cathode	11
Production Li/Na Electrolyte Powder	11
Production Furnace Sintering Trials	11
Laboratory Furnance Modifications	11
Low Cr Anodes	12
Subtask 3.6: Quality Assurance/Quality Control	12
Definition of Quality Program Requirements	12

TABLE OF CONTENTS

<u>Item</u>	<u>Page</u>
Development of QA/QC Procedures and Methods	12
Subtask 3.7: Analytical Testing	13
Identification of Analytical Requirements	13
QA/QC Equipment Maintenance	13
TASK 4: PACKAGING AND ASSEMBLY	13
Subtask 4.1: Packaging Methodology Improvements	14
Subtask 4.2: Packaging Methodology Verification	14
Subtask 4.3: Assembly Methodology Improvements	14
Subtask 4.4: Assembly Methodology Verification	14
Subtask 4.5: Conceptual Assembly Factory Design	14
TASK 5: TEST FACILITIES	14
Subtask 5.1: Cell & Subscale Stack Test Facilities	15
Maintain 20kW Atmospheric Test Facility	15
Maintain Acceptance Test Facility (ATF)	15
Develop Pressurized Bench Scale Facility	16
100 cm ² Cell Test IM9503	16
100 cm ² Cell Test IM9504	16
100 cm ² Cell Test M0195003	16
100 cm ² Cell Test M0196001	16
100 cm ² Cell Test M0196002	17
100 cm ² Cell Test IM9601	17
100 cm ² Cell Test IM9602	17
General Test Facility Maintenance	17
Subtask 5.2: Stack Module Verification Facility	18
Review and Update 250kW Facility	18
Subtask 5.3: Power Plant Shipping Design	18
Subtask 5.4: Upgrade Unocal Facility to 500 kW	18
TASK 6: TECHNOLOGY DEVELOPMENT, IMPROVEMENT AND VERIFICATION	18
Subtask 6.1: Cell Package	19
Active Component Unit Improvement	19
Introduction	19
Phase Diagram Studies	19
MCFC Tests	21
Improved Cathode Performance	23
Alternate Electrolyte	24
Strengthened Anode Fabrication	24
Cathode Dissolution	24
Alternate Cell Package Development	25
Advanced Cell Package Fabrication	26
Decrease Cathode Tortuosity	26
Thin Anodes	26
Cathode Depolarization	27
Analytical Results	29
Bench Scale Testing	29

TABLE OF CONTENTS

<u>Item</u>	<u>Page</u>
Cell IGT-BS-TC-42-96-1	29
Cell IGT-BS-TC-42-96-2	34
Cell IGT-PDI-5	35
Cell IGT-PDI-6	36
Cell IGT-PDI-8	37
Cell IM9504	38
Cell IM9601	39
Subtask 6.2: Fuel Cell Module	40
Subtask 6.3: Balance of Plant Component Development	40
Subtask 6.4: Full Area Stack Tests	41
Fabricate and Operate 20kW Non Pressurized Stacks	41
Stack Failure Mode Verification	41
Subtask 6.5: MW-Class Power Plant Demonstration	41
Subtask 6.6: Update Commercialization Plan	41
Appendix A: ISO 9001 Quality Assurance	42
Appendix B: Analytical Testing	43
DESCRIPTION OF ATTACHMENTS	44
CONTRACT REPORT TRANSMITTAL CHECKLIST	45

LIST OF FIGURES

<u>Figure No.</u>	<u>Page</u>
Figure 1: Resistivity vs CO ₂ Mole Fraction for LiCoO ₂ -LiFeO Solid Solution ₂	20
Figure 2: Resistivity vs Mole Fraction CO ₂ For LicoO ₂ -LiFeO ₂ -NiO Solid Solutions. Material Composition (in m/o): #1: 70 LiFeO ₂ , 25 NiO and 5 LiCoO ₂ ; #2: 70 LiFeO ₂ , 21.5 NiO and 8.5 LiCoO ₂ ...	21
Figure 3: Cell Voltage vs Time For A Cell Containing A Cathode of Material 1	22
Figure 4: Cell Polarization Curves vs Time For Cell Containing A Cathode of Material 1	22
Figure 5: Cell Area-Specific Resistance (ASR) vs CO ₂ Mole Fraction For Cell Containing A Cathode of Material	23
Figure 6.1.1.4.2.1: Life Plot of Cell IGT-BS-TC-42-96-2	34
Figure 6.1.1.3.3.1: Life Plot of Cell IGT-PDI-5	35
Figure 6.1.1.4.3.2: Life Plot of Cell IGT-PDI-6	36
Figure 6.1.1.4.3.3: Life Plot of Cell IGT-PDI-8	38
Figure 6.1.1.4.3.4: Power Output As A Function of Current Density For Cell IGT-PDI-8 (At 3 atm Pressure, 75% U _F and 40% U ₀)	39
Figure 6.1.1.4.4.1: Life Plot of Cell IM9601	40

Statement of Cooperative Agreement Objectives

The primary objective of this effort is to establish, by 1998, the commercial readiness of MW-class IMHEX® MCFC power plants for distributed generation, cogeneration, and compressor station applications. Commercial readiness will require an advanced IMHEX® technology base, lower-cost manufacturing processes, verified balance-of-plant components, proven packaging and assembly approaches, demonstrated prototype power plants, finalized manufacturing and market distribution plans and a committed commercialization team. The M-C Power Team's supporting objectives are:

- To finalize product definition, complete detailed product design, identify and evaluate balance-of-plant components, and generate power plant manufacturing and market distribution plans which will result in successful transition from development into commercial market entry;
- ▶ To develop and optimize fuel cell component manufacturing processes and power plant assembly and packaging methodologies which will provide a market-responsive MW-class power plant in low production volumes appropriate for the initial stages of commercialization;
- ▶ To advance and improve the IMHEX® stack technology, balance-of-plant components, and power plant integration which will provide the technology basis for a reliable, cost-effective MW-class product;
- ▶ To demonstrate and verify the reliability, performance, and cost-effectiveness of these technologies in a prototype IMHEX® fuel cell power plant which will establish the marketplace confidence needed for successful entry into the commercial market; and
- To establish the necessary infrastructure and strategic alliances with vendors/suppliers to support market entry and commercialization.

The work to be performed by M-C Power and the subcontractors is divided into the six tasks listed below. The objectives for each task, along with a brief update, where appropriate, is shown on the following pages, which constitutes this technical report. A breakdown of the subtasks is included in this report.

Task 1:	Product Definition and Planning
Task 2:	System Design and Analysis
Task 3:	Manufacturing Process Development
Task 4:	Packaging and Assembly
Task 5:	Test Facility Development
Task 6:	Technology Development, Improvement, and Verification

Summary of Work Accomplished During the Reporting Period By Task (1/1/96 - 3/31/96)

TASK 1 PRODUCT DEFINITION AND PLANNING

Objective: The objectives of this task are to provide the product definition and plans necessary to ensure that the MW-class power plant developed and verified during this activity is responsive to the marketplace needs and conforms to M-C Power's existing Commercialization Plan and to prepare a report to satisfy the requirements of the National Environmental Policy Act.

Subtask 1.1 Identify Requirements

Objective: The contractor shall update existing product requirements based on marketplace input and document the requirements of a MW-class market-responsive MCFC power plant through market surveys, product option evaluations, and analysis of applicable codes and regulations. The contractor shall prepare a market analysis report that identifies product requirements, analyzes the survey results, and identifies applicable codes and regulations.

Status: Analyze Market Surveys, Codes and Regulations
Inactive during this reporting period. Scope of work for Budget Period II has been discussed with Bechtel.

Subtask 1.2 Generate Product Definitions

Objective: The contractor shall generate product options based on market requirements and technical feasibility, select a market entry product approach based on its cost-effectiveness and market responsiveness, and prepare a product description document.

Status: Product Marketing Efforts
M-C Power has placed a subcontract with the Alliance to Commercial Carbonate Technology (ACT) to do a study for the early adopters program.

Subtask 1.3 Product Goals

Objective: M-C Power will develop product goals that will be used to measure the progress and success of specific development activities and to redirect the development efforts as appropriate. Specifically, M-C Power will develop performance goals, life goals and cost goals.

Status: *This subtask is complete.*

Subtask 1.4 Commercialization Plans

Objective: M-C Power will develop a commercialization business plan which addresses those steps taken to develop/obtain the competencies (packaging, distribution, sales and services) to commercialize the MCFC technology based on the market surveys and product definition work completed in previous tasks.

Status: *This subtask is complete.*

Subtask 1.5 **Task Management & Reporting**

Objective: M-C Power and its contractors will perform general management efforts, prepare required financial, schedule and management reports as required. Also, work necessary to keep management information up to date will be performed.

Status: *Monthly and quarterly reports have been submitted to the DOE for the PDI cooperative agreement as specified within the agreement. Also, M-C Power prepares and submits a weekly report to D. Hooie, of the DOE, which provides additional information on the PDI project, where appropriate.*

TASK 2 **SYSTEM DESIGN AND ANALYSIS**

Objective: The objective of this task is to conduct a system optimization study to evaluate various process options for maximizing plant performance and minimizing plant cost of the commercial unit. Based on the selected operating parameters and plant configuration, a preliminary design and cost estimate will be prepared to analyze the overall plant performance and economics.

Subtask 2.1 **Power Plant System Optimization**

Objective: To meet performance and cost targets for market-entry fuel cell power plants. The current design will be technically optimized through trade off studies and then analyzed and optimized to reduce material, labor, equipment, site installation, and operating costs.

Status: *This subtask is complete.*

Subtask 2.2 **Generate Preliminary Design**

Objective: Based on the process configuration selected in task 2.1, Bechtel will prepare a preliminary design for the commercial unit. Bechtel will confirm, jointly with DOE and M-C Power, the design basis to be used. The basis of the design will follow the product definitions established in task 1.

Status: **Power Plant Process Design**

Bechtel evaluated the impact of the new lower seal differential pressure from M-C Power on the loose-case design and the entrant pressure case design. The results indicate that future improvement on seal design to increase the allowable differential pressure to the desired level will be necessary prior to commercialization.

Power Plant System Engineering

Bechtel verified that the new stack simulation model does automatically adjust the user input anode feed to meet water shift equilibrium at the input temperature. By ignoring the heat of reaction associated with the water shift, the new stack model underestimates the required heat rejection from the fuel cell stack. It is agreed that the heat imbalance is sufficiently small so that the new model can be used for our current work. Bechtel is

integrating its heat and material balance calculations with the new fuel cell stack simulation program.

Because of the higher air and cathode inlet temperature requirement, the original base case scheme is no longer valid. The makeup air compressor cannot be driven by cathode exhaust because the exhaust have to preheat the makeup air prior to power recovery. We are now reviewing the process trade-off study to include impact of pressure varying, intercooler vs cathode recycle, hot vs cold cathode recycle, and various seal differential pressure reduction schemes.

Subtask 2.3 Detailed Cost Estimate

Objective: In this task, a detailed capital and operating cost estimate will be generated based on the design developed in Subtask 2.2.

Status: *The completion of this substack is dependent on the finalization of the design work being done is subtask 2.2.*

Subtask 2.4 Performance Analysis

Objective: The power plant performance will be simulated and evaluated for a range of operating states and conditions. Reliability, availability, maintainability, and safety will be assessed.

Status: Power Plant Dynamic Simulations
Inactive during this reporting period.

TASK 3 MANUFACTURING PROCESS DEVELOPMENT

Objective: The objectives of this task are to reduce stack costs and improve quality by optimizing existing cell and stack manufacturing processing, assessing and implementing in-house processing of separator plates, implementing advanced, high-speed low-cost cell manufacturing processes, and to design a conceptual stack manufacturing factory.

Subtask 3.1 Cell Component Manufacturing Process Simulation

Objective: Active component manufacturing processes will be optimized through the use of simulations, modeling, and testing and implemented to reduce cost, increase through-put, and improve quality of the baseline manufacturing processes.

Status: Computerized Cell Component Manufacturing Process Simulation
M-C Power has developed a manufacturing process simulation that is being used to conduct "What -if" analysis.

Automate Current Cell Component Manufacturing

M-C Power is in the process of completing a major rebuild and upgrade of the sintering furnace. During the past quarter, M-C Power has been working with the furnace vendor in trouble shooting the modifications. The trouble shooting and testing work is expected to continue in the second quarter.

Subtask 3.2 **Cell Stack Hardware Manufacturing**

Objective: Existing plate processing and fabrication techniques will be evaluated. Appropriate technologies and equipment will be implemented and brought in-house to improve quality control and reduce cost.

Status: *This subtask is ongoing.*

Subtask 3.3 **Develop Advanced Manufacturing Processes (Cell/Stack Components)**

Objective: The market entry product potentially requires advancements in the baseline manufacturing processes currently being utilized and optimized. Optimizations being implemented are projected to reduce stack costs to below \$4,000/kW in low production volumes. To achieve the \$430/kW cost target for market entry, advanced processes and designs need to be evaluated and qualified. The objective of this task is to identify, evaluate, and qualify potential advanced processes.

Status: *Develop Advanced Manufacturing Processes*
Electrode samples have been thermally sprayed, which yielded porosities that are unacceptable. M-C Power is currently investigating powders with different particle morphology so that sprayed electrodes will have the desired microstructures.

Subtask 3.4 **Manufacturing Process Scale Up**

Objective: Manufacturing system simulations will be used to define scale-up goals and achievable targets for the advanced processes qualified and selected in Task 3.3.

Status: *This subtask is ongoing.*

Subtask 3.5 **Cost Reduction**

Objective: The contractor shall evaluate and implement stack cost reduction technologies including recycling of materials, recovery of processed raw materials and recycling, implementing advanced component technologies, and verifying advanced plate engineering designs and concepts.

Status: *Cost Reduction*
Obtained input regarding the effects of impurities on cell performance. This data will be utilized to evaluate the use of lower cost, lower grade materials for a future 100-cm² cell test.

The vendor which supplies the electrolyte powder was contacted concerning avenues to lower the cost of the electrolyte powder. The melt characteristics of a lower cost electrolyte are being investigated to determine of the acceptability of their use for benchscale cell test IM9602. Two tapes were successfully cast on the benchtop. Improved tape properties were

obtained for powder milled to particle sizes typically utilized for the current production electrolyte powder. Trials were completed to characterize the melt characteristics of the lower cost electrolyte tapes.

Lower Cost Stabilized Cathode

Materials were ordered and received for the full area manufacturing trials scheduled for the second quarter of 1996. A lower cost stabilized cathode was cast for sintering trials. The porosimetry of the sintered components will be used to evaluate the possibility of replacing the nickel powder currently specified for the "Low Cost Stabilized Cathode" with an even lower cost alternative.

Stabilized Cathodes

Benchtop casting trials were initiated for finalizing the formulations which will be utilized during the scale up efforts. Formulations and procedures for solvent based casting and water-based casting of the stabilized cathode are being evaluated. Three stabilized cathode tape formulations were cast for sintering trials.

Stabilized cathode tapes were cast for initial scale up to full area evaluations. Samples were cut and reserved for scale up sintering trials currently scheduled for March-April of this year.

Production Li/Na Electrolyte Powder

Melt tests of the production Li/Na electrolyte were completed with an electrolyte sample for comparison. The Li/Na powder produced a melt which is orange compared to the Li/K melt. Widely scattered dark foreign impurities are present in the Li/Na sample. The analytical results of the Li/Na production powder were received and reviewed.

Li/Na tapes were successfully cast this month, scaling up from the narrower doctor blade. As-cast measurements were completed. These casts will be used as a baseline for scale up to full area casts. The tapes were sectioned for use in upcoming PDI 100-cm² and 1000-cm² cell tests.

Production Furnace Sintering Trials

Low Cr anodes and lower cost stabilized cathodes were sintered in the production furnace this week in 100% nitrogen at belt speeds of 2" and 3"/minute. A much higher degree of sintering is occurring than obtained previous to the retrofit.

Laboratory Furnace Modifications

The installation of a hydrator into the laboratory furnace was completed. This will enable sintering/binder removal in humidified atmospheres similar to those utilized in the production furnace.

Low Cr Anodes

Began preparing the milled chromium solution for scale up activities of the low Cr anode which will occur after the production furnace is operational (second quarter of 1996) and has been broken in with the standard PDI-type anodes.

Subtask 3.6

Quality Assurance/Quality Control

Objective:

M-C Power has chosen to follow the American National Standard/American Society for Quality Control (ANSI/ASQC) Q91-1987 quality standard, a technical equivalent of the International Standards Organization (ISO) 9001 standard, ("Quality Systems - Model for Quality Assurance in Design/Development, Production, Installation, and Servicing"). The Q91 standard provides requirements for quality program development and maintenance, while allowing the flexibility to meet the specific needs of M-C Power. ISO registration is planned.

Status:

Definition of Quality Program Requirements

M-C Power is in the process of updating and implementing QA/QC procedures and methods. More specific, detailed information will be provided as it becomes available.

A plan for the development and implementation of the M-C Power Quality program was defined in the context of the ISO 9001 quality standard. An outline of the issues to be addressed in attached as Appendix "A". This plan is based on the requirements of the standard, taking into consideration the developmental aspects of most M-C Power operations. A procedure for the review and approval of the ISO procedures was developed and approved by upper management, in which all documents will receive written approval by upper management, while the review process will focus on the line supervisors.

The plan was developed to take into account past experience at M-C Power. Much of the focus to date has been on identifying the causes of past nonconformances. The plan puts a new priority on initial design issues, such that the means of recognizing process limitations, cost, and schedule constraints is integrated into design considerations, such that quality requirements can realistically be met.

Development of QA/QC Procedures and Methods

Quality procedure development and documentation has proceeded and numerous operating procedures were developed and implemented for quality assurance, testing, and analytical functions. A list of the procedures developed and implemented to date is included as Appendix "B". A primary intent of these procedures has been to standardize those activities in which several individuals and groups may be involved. Where appropriate, inspection and testing procedures were verified through the application of repeatability and reproducibility trials, often involving several employees. Training in the use of these procedure was also performed for the more complex technical procedures, such as the operation of the stack gas analytical system and the coordinate measurement machine. In both of these instances, employee certification programs were implemented to ensure that personnel operating these systems were adequately trained in the use of the operating procedures.

The majority of the procedures developed were technical in nature. Some procedures were instituted to address more "administrative" aspects of the quality program, such as a drawing review procedure, procedures for the disposition of nonconforming materials, incoming inspection requirements, etc. Future work will focus more on this type of procedure rather than the more technical operating procedures.

Subtask 3.7
Objective:

Analytical Testing

Improvement and upgrading of analytical capabilities has been ongoing at M-C Power and investigation into new or improved analytical methods to meet the increasing analytical needs in a cost-effective and timely way has been a priority and will be addressed in a systematic approach.

Identification of Analytical Requirements

Based on ongoing development activities, several issues pertaining to future analytical requirements were identified. An assessment of future needs will be performed to determine the most feasible and cost-effective way of performing these analyses. The upcoming analytical needs identified to date included methods for the analysis of sodium for new electrolyte formulations, calcium for developmental cathodes, and a method for particle size assessment to facilitate the certification of incoming powders for active component manufacturing.

QA/OC Equipment Maintenance

This work includes the repair and routine maintenance of Government-owned equipment, such as the coordinate measuring machine (CMM) and stack gas analyzers. Activities performed during the past reporting period included several repairs and parts replacement for the gas chromatographs used for stack gas analyses, and the stocking of critical spare parts to minimize downtime during stack testing operations. Additionally, preventive maintenance plans were documented for the major equipment, such as the gas analytical system and the CMM. Implementation of such preventive maintenance has reduce equipment downtime from previous years and reduced the cost for in-house repairs and vendor service calls, particularly in the case of the CMM, where annual vendor calibration and maintenance has eliminated the need for service calls over the past year.

TASK 4

Objective:

PACKAGING AND ASSEMBLY

The objectives of this task are to improve and verify efficient and low-cost packaging and assembly methodology for the BOP and the stack module and to design a conceptual power plant factory.

Subtask 4.1 **Packaging Methodology Improvements**

Objective: The packaging of the fuel cell stack and the balance of plant has a significant impact on the size, weight, cost, and heat loss. Mechanical integration will reduce cost and increase efficiency by reducing heat losses.

Status: *Inactive this reporting period.*

Subtask 4.2 **Packaging Methodology Verification**

Objective: A scale model will be produced to verify the configuration and the packaging method prior to manufacturing. The performance of advanced gas distribution manifolds will be verified through simulated tests to check that the proper flow distribution is attained.

Status: *Inactive this reporting period.*

Subtask 4.3 **Assembly Methodology Improvements**

Objective: Assembly methods for the BOP equipment will be improved. Predictability studies will be conducted during the specification and design phase. Design parameters affecting material selection, fit-up, and tolerances will be verified. The cost effectiveness of automated welding will be assessed. Production tooling will be developed and cost effective acceptance testing for various components and the system prior to shipment will be determined.

Status: *Inactive this reporting period.*

Subtask 4.4 **Assembly Methodology Verification**

Objective: Stack assembly methodology will be verified through a trial assembly and fit-up on the proposed automatic cell stacking machine. A three-dimensional computer model of the BOP mechanical skid, fuel cell power module, and the electrical module will be generated to verify the assembly approaches for the construction of the MW-class power plant.

Status: *Inactive this reporting period.*

Subtask 4.5 **Conceptual Assembly Factory Design**

Objective: A conceptual design of a packaging and assembly plant will be developed based on the production level and product definitions necessary to meet market requirements.

Status: *Inactive this reporting period.*

TASK 5 **TEST FACILITIES**

Objective: The objective of this task is to provide the facilities necessary to support cell technology and stack verification and power plant distribution. The facilities will consist of new facilities and upgraded existing facilities.

Subtask 5.1 **Cell & Subscale Stack Test Facilities**

Objective: Cell and stack test facilities are required for verification of cell component performance and durability and confirmation of cell and stack designs.

Status: **Maintain 20kW Atmospheric Test Facility**

The bellows and force plate from the test clamping fixture were and moved into the stack room for storage. The anode end plate from MCP-7 had the piping connection hardware removed. The anode and cathode end plates from the MCP-7 test were moved to the 8100 building for storage.

Maintain Acceptance Test Facility (ATF)

This quarter preparation of the test facility for the PDT-1 and PDI-1 stack conditioning and acceptance testing was started. Cross piping across the anode and cathode process gas feed piping to the stack effluent piping was installed to allow cold facility process and control testing. Equipment operating verification checks of the various control valves, heaters, rotating equipment was completed.

Modifications for the replacement of the stack enclosure furnace control thermocouples in case of failure during conditioning operation was developed, and new improved specification replacement thermocouples were ordered and received. This task is being undertaken to improve the control performance of the furnace in the stack electrolyte melting operation. The thermocouples purchased are 1/4" mineral sheath with matched lot construction. Modification of the access covers located on the outside of the enclosure furnace for thermocouple maintenance was completed.

Initially the test facility failed to meet the recycle flow requirements for stack conditioning for both the anode and cathode stack feeds during the first cold flow test conducted. The low recycle flow rates were determined to be caused by the very low differential pressures that could be achieved by the recycle blowers during this test. Further investigation and testing of the recycle blowers and the related process control and equipment configuration revealed several problems related to the installation of the automatic blower bypass valving. Both the anode and cathode bypass valves were found to be installed opposite the manufactures preferred flow direction. In addition, the valves were being cycled in the wrong direction for full flow blocking operation. These problems were corrected and a second cold flow test was conducted to confirm that the work on the recycle blower bypass valves would allow facility operation at required recycle flow rates. Both the anode and cathode required feed flows were obtained.

During the test conducted equipment operation and start up procedures from the draft facility operating manual were verified and refined. The start up procedures for the facility recycle blowers are in the process of being verified and fine tuned.

The start up procedure for the water recirculation system was verified and modified to account for the system changes made since the initial installation and procedure development. All identified control programming change requirements were completed and a third cold flow test completed in preparation of the conditioning and testing of the PDT-1 stack assembly. This test was used to verify and fine tune anode and cathode recycle blower start up procedures, check the operation the control program changes, and system interlock operation.

Pre-test verification and documentation of both process heaters and heating cables status was completed. One heating cable on the water injection line was found defective and was replaced with a pre-installed spare heating cable. Maintenance documentation for periodic and pretest maintenance of equipment and instrumentation is being developed as required during facility test preparation activities. Installation of the new stack enclosure furnace thermocouples will be completed next month.

Work on preparation of a draft facility operating manual as started this quarter. The draft operating manual being developed covers basic equipment start up and operation and will be used for operator training and equipment operation for the PDT-1 stack conditioning and test operations.

Develop Pressurized Bench-Scale Facility

Several tests have been started this year under the PDI program. Updates on these tests are shown below.

100 cm² Cell Test IM9503

Post test sample separation was completed and samples were sent for analysis.

100 cm² Cell Test IM9504

This test was terminated on 2/25/96 after only 840 hours of operation due to low performance blamed on polarization losses: the performance of 688 mV at 160 mA/cm² and 60% $U_{t_{fuel}}$ on system gases pressurized to 3 atm was ~60 mV lower than that obtained for Cell IGT-BSTC-66-94-1 under similar conditions. This was a pressurized test of a stabilized cathode, low Cr anode, and Li/Na electrolyte system and a duplicate of cell test IGT-BSTC-66-94-1 which ran for 7000 hours of pressurized operation.

The gas access side of the anode was smooth and much denser than that facing the matrix layers due to roll compaction of the low Cr anode during manufacture. The low performance may have been due inhibited gas access to the anode.

100 cm² Cell Test M0195003

This test completed 7508 hours of operation as of 4/5/96 and continues steady operation at 766 mV at 160 mA/cm² and 60% $U_{t_{fuel}}$ on system gases pressurized to 3 atm (life graph attached).

This test includes the first Li/Na electrolyte tested at M-C Power and a lower cost version of the stabilized cathode. Problems in maintaining control of the cathode pressure were resolved. Modification of the test stand will be completed to prevent a recurrence of the cathode overpressure incidents. The test experienced three power outages this quarter, the cell OCV returned to normal values before reloading the cell each time. Polarization and cell internal resistance measurements were conducted for comparison to previous data. Cell internal resistance has remained stable at 2.8 m Ω . The data indicates a slight decrease in the performance at 75% $U_{t_{fuel}}$ with a calculated decay rate of 4.5 mV/1000 hours. The decay rate at 60% $U_{t_{fuel}}$ has been negligible.

100 cm² Cell Test M0196001

This test is a twin cell of the PDI-1 (250 kW stack) components with the purpose of evaluating advanced cell conditioning procedures and provide benchmark performance

levels for ATF and power plant operation conditions. Cell performance testing at ATF and baseline conditions at 1 atm were completed. Both the cell resistance and the baseline performance data are acceptable. This test completed a thermal cycle to room temperature after successful cell performance testing at ATF and baseline conditions at 1 atm. The cell performance was very low: ~ 100 mV below pre-thermal cycle performance with recovery to within ~25 mV of the pre-thermal cycle values after soft start procedures. Hot hold test condition testing began after pressurization to 3 atm. This test will continue into next quarter.

100 cm² Cell Test M0196002

Part selection and carbonate loading were completed for this cell and the cell is ready for testing pending completion of the M0196001 test. This test will be a twin cell of the PDI-1 (250 kW stack) components with a proposed change in the startup procedure and gas compositions, based on the results of the M0196001 test.

100 cm² Cell Test IM9601

Components for this cell test were manufactured and delivered to IGT for testing this quarter. The active area component selection, component matching, carbonate loading and pre-test report were completed. Cell test IM9601 completed 672 hours of operation as of 4/5/96 with a performance of 768 mV at 160 mA/cm² and 60% U_{fuel} on system gases pressurized to 3 atm (life graph attached). This is a test of a Ni-Al alloy anode with the Li/Na electrolyte system. The component characteristics were altered from those tested in IM9502 to improve the carbonate matching of the components. This performance is ~16 mV higher than that obtained for cell IM9502 under similar conditions.

100 cm² Cell Test IM9602

This 100-cm² cell test will evaluate a significantly lower cost electrolyte, a lower cost stabilized cathode and matrices compared to the current components utilized for the PDI-1 stack and for the stabilized cell package currently slated for scale up. Active area components were manufactured for this test and the pretest report and test plan were completed. Cell start up was initiated this week.

General Test Facility Maintenance

The following activities are part of the Acceptance Test Facility (ATF) job completion items.

- A meeting was held on January 25th to review the recommended piping modifications from a pipe stress analysis firm, which include pipe supports, stops and spring cans. As a result of this meeting all of the new spring cans and pipe supports specified were ordered.
- Piping modifications were stated on February 13th and completed on February 26th.
- The final pipe insulation installation began on March 4th and was completed on March 15th. The long duration to perform the work was driven by the procurement of the Microtherm material that was due by the close proximity of the cathode inlet pipe to the structural steel. This concluded the repair work to the equipment skids.

- *Information was received from the manufacturer of HTR-6075, that showed the nozzle loads from the analysis conducted are acceptable and will not overload the nozzles of HTR-6075.*
- *The final mechanical drawings have been received on disk and will be used in the Operators Training Manual.*

Work has been initiated to modify the existing crossover pipes in the ATF to allow for a hot test of the equipment at operating conditions. A quotation to perform this work is expected during the first week in April.

M-C Power has found the glitch in the automatic by-pass valve software. The by-pass valves now work in the automatic mode. Final electrical work was completed on February 8th. If time permits, the time to open the valves will be reduced. It presently takes about two (2) seconds to open.

The practice assembly of the anode condensate water system for the ATF was completed the week of February 12th. After assembly, the system was disconnected to prevent damage prior to the system being needed for the SDG&E-1 stack.

M-C Power has completed the final instrumentation calibration checks in the ATF. The only equipment that remains to be checked in the ATF are the water injection pumps.

Subtask 5.2

Stack Module Verification Facility

Objective:

The existing 250kW partially integrated facility at Unocal will be used to test an additional 250 kW stack under this program.

Status:

Review and Update 250-kW Facility

M-C Power is investigating and finalizing the Scope of Work required to change the Unocal facility to a 250 kW Test Facility.

Subtask 5.3

Power Plant Shipping Design

Objective:

Building upon the experience of Unocal and SDG&E, this task will concentrate on identifying and quantifying the shock and vibration limits so that means of transportation can be devised.

Status:

Inactive during this reporting period.

Subtask 5.4

Upgrade Unocal Facility to 500kW

Objective:

This task is involved with the modifications required to the Unocal power plant to accept future stacks up to 500kW in size.

Status:

Inactive during this reporting period.

TASK 6

TECHNOLOGY DEVELOPMENT, IMPROVEMENT AND VERIFICATION

Objective:

The overall objective of this task is to provide the cell, stack, and BOP component technology developments, improvements and verifications and to provide the power plant product verification to bring a multi-fueled, integrated, simple, low-cost, modular, market-responsive IMHEX[®] molten carbonate fuel cell power plant to the marketplace. This task includes design,

fabrication, construction, testing, and analysis of a MW-class (nominal 1 MW) power plant demonstration.

Subtask 6.1 **Cell Package**

Objective: The contractor shall improve cell package cost, performance, stability, and durability using evolutionary approaches with existing technology and innovative approaches to achieve breakthroughs. Materials, geometrics, and microstructures will be addressed. Out-of-cell, single-cell, and subscale stack tests will be used to verify and implement improvements. The contractor shall address cathode dissolution and performance, cell sealing, thermal cycling, cell package simplification, cost reduction, and component strengthening.

Status: **Active Component Unit Improvement**

Effort concentrated on alternate cathode development at Argonne National Laboratory.

Introduction

Argonne National Laboratory is developing advanced cathodes for pressurized operation of the molten carbonate fuel cell (MCFC).

Studies of the $\text{LiFeO}_2\text{-LiCoO}_2\text{-NiO}$ phase diagram are being conducted to aid in optimizing the doubly doped LiFeO_2 cathode. Resistivities of $\text{LiFeO}_2\text{-LiCoO}_2$ and $\text{LiFeO}_2\text{-LiCoO}_2\text{-NiO}$ solid solutions are presented. One of these compositions (70m/o LiFeO_2 , 21.5 NiO and 8.5 LiCoO_2) has a resistivity close to that of LiCoO_2 and is, therefore, expected to perform very well in an upcoming cell test.

Argonne National Laboratory is developing advanced cathodes for pressurized operation of the molten carbonate fuel cell (MCFC). Alternative cathodes based on lithium ferrate (LiFeO_2) and lithium cobaltate (LiCoO_2) are less soluble than nickel oxide. However, the LiFeO_2 cathode, because of its high resistivity (about 300 $\Omega\text{-cm}$), cannot be employed as a direct substitute for the lithiated NiO cathode, which has a resistivity of about 0.1 $\Omega\text{-cm}$. Instead, dopants are required to improve the resistivity of the LiFeO_2 cathode to an acceptable level (about 1 $\Omega\text{-cm}$); development of an appropriate combination of dopants was the focus of much of prior work.

In the last quarterly report, a preliminary phase diagram for the $\text{LiFeO}_2\text{-LiCoO}_2\text{-NiO}$ system was presented. The data indicated that a continuous solid solution exists along the NiO- LiFeO_2 join. As expected, the Resistivities of the NiO- LiFeO_2 materials decreased with NiO additions. On the $\text{LiCoO}_2\text{-LiFeO}_2$ join, there are two regions of homogeneity: 0-6 and 87.5-100 m/o LiCoO_2 . The region of homogeneity in the ternary system extends from the NiO- LiFeO_2 binary to a LiCoO_2 concentration of about 10-12 m/o

In this quarterly report, recent studies of the regions of homogeneity in the $\text{LiFeO}_2\text{-NiO}$ phase diagram are presented. Resistivity data from selected solid solutions is also presented. Some MCFC performance data is also discussed.

PHASE DIAGRAM STUDIES

The solubilities of NiO and LiCoO_2 in LiFeO_2 are being measured to aid in optimizing the doubly doped LiFeO_2 cathode composition. Adding small amounts of LiCoO_2 to LiFeO_2 markedly decreases the resistivity of LiFeO_2 . For example, adding 6m/o LiCoO_2 to LiFeO_2 decreases the resistivity from 300 to about 5 Ωcm at 650° C. Adding still more LiCoO_2 to LiFeO_2 further decreases resistivity. With 12.5 m/o LiCoO_2 , the resistivity is 3 Ωcm . The trend in resistivity of the solid solutions with LiCoO_2 additions is depicted in Figure 1 along with the dependence of resistivity on CO_2 mole fraction. Interestingly, the changes

in resistivity with CO_2 (which have been seen in other LiFeO_2 - LiCoO_2 - NiO materials) became less obvious with LiCoO_2 additions.

FIGURE 1
Resistivity vs CO_2 Mole Fraction For LiCoO_2 - LiFeO_2 Solid Solutions

Two high LiFeO_2 ternary materials were made and characterized in terms of resistivity versus CO_2 mole fraction. These compositions are (in m/o): 70 LiFeO_2 , 25 NiO , and 5 LiCoO_2 ; and 70 LiFeO_2 , 21.5 NiO , and 8.5 LiCoO_2 . The Resistivities of these materials, denoted as numbers 1 and 2, respectively, are given in Figure 2. The increased LiCoO_2 concentration decreases the overall resistivity of the material and, from the difference in slopes of these lines, decreases the dependence of resistivity on CO_2 mole fraction. The resistivity of Material is 1.3 Ωcm at 650° C; this value is close that of pure LiCoO_2 (1 Ωcm at 650° C).

FIGURE 2
Resistivity vs. Mole Fraction CO_2 For LiCoO_2 - LiFeO_2 - NiO Solid Solutions.
Material Composition (in m/o): #1: 70 LiFeO_2 , 25 NiO and 5 LiCoO_2 ;
#2: 70 LiFeO_2 , 21.5 NiO and 8.5 LiCoO_2

MCFC TESTS

A 5 x 5-cm MCFC test is in progress using Material 1. The oxidant consists of 60-70% O_2 and 30-40% CO_2 . The cell potential at 160 mA/cm^2 vs time is given in Figure 3. Figure 3 shows that, after a relatively short period, the cell potential is stable at 0.82 V. Polarization and cell area-specific resistance (ASR) vs CO_2 mole fraction curves were measured periodically during test. The polarization curve (Figure 4) indicates that the cell behavior is becoming less ohmic with time. Cell ASR (Figure 5) has decreased to less than 1 $\Omega\text{-cm}^2$ after about 500 h.

In previous cell tests using doubly-doped materials, Co migration was observed. We think the transport was due to free LiCoO^2 in the two-phase cathode. The current cell uses the single-phase cathode, Material 1. After 2000 h or cell failure, the cell will be examined to determine the extent of Co transport. A cell test is planned for Material 2.

FIGURE 3
Cell Voltage vs Time For A Cell Containing A Cathode of Material 1

FIGURE 4
Cell Polarization Curves vs Time For Cell Containing A Cathode of Material 1

FIGURE 5

Cell Area-Specific Resistance (ASR) vs CO₂ Mole Fraction For Cell Containing A Cathode of Material 1

Improved Cathode Performance

According to the cathode performance model, only 1/8 of the available cathode surface area is participating in the electrochemical reactions. If this needed the case, significant improvement in cell performance (as much as 40 mV) can be gained by increasing the active cathode surface area. The effect on cell performance of active cathode surface area is clear. In 1993, it was demonstrated that cell performance at 1 atm with reference gases as 160 mA/cm² improved by at least 20 mV when the Ni loading of the cathode was increased from 20 to 30%. A higher loading will result in a tighter cathode pore structure and will be difficult to match with the pores of the anode and/or the matrix. Therefore, further improvement in cathode performance has to be obtained by improving the cathode microstructure. The Ni loading of 30% is the maximum for the cathode.

The carbonate that is wicked into the cathode fills up the micropores within the agglomerates first and then covers the surface of the agglomerates with carbonate film. The film covered surface of the agglomerates is the active surface of the cathode. The smaller the agglomerates, the larger the active surface. Unfortunately, to design the cathode with smaller agglomerates (for increased surface area) without increasing the porosity (or decreasing the Ni loading), the pores between agglomerates will also be reduced. Additionally, the pores must have minimum tortuosity (i.e. more straight through the cathode thickness). Therefore, the agglomerate the size, porosity, and pore tortuosity have to be optimized.

Optimization techniques are being investigated. The desired cathode microstructure have been nearly obtained and coupons are being analyzed for compaction and sintering properties.

Alternate Electrolyte

In 1995, the Li/Na electrolyte has become the standard electrolyte for IGT bench scale cells because of its high and stable performance. The technology has been transferred to M-C Power and is being scaled up. Additional improvement in cell performance will have to be provided by improvements in cathode pore structure design as discussed under Subtask 6.1.1.3.3.

This quarter, we terminated and analyzed post test components of Cells IGT-BS-TC-66-93-4, PDI-2, and IGT-BS-TC-42-95-5. These cells used Li/Na electrolyte.

After about two years of operation, Cell IGT-BS-TC-66-93-4 was terminated because of increasing decay rate. There is no evidence of cell shorting by Ni deposits in the matrix due to cathode dissolution from this 2-year cell.

Cells PDI-1 and PDI-2 had aluminized flanges covering not only the wet seal area but also the vertical exterior surfaces. The aluminized exterior surfaces promoted carbonate creepage and the cells had a high rate of carbonate loss. This was the cause of their high decay rates. Therefore, aluminization will be confirmed only to the wet seal area. PDI-1 also had a cathode with a low porosity, and therefore, with a tight pore structure that became flooded with electrolyte.

Cell IGT-BS-TC-42-95-5 was a test for a pre-conditioned cathode current collector/cathode/matrix laminate. The cell performed poorly, reaching just 532 mV at 160 mA/cm² on reference gases. The cause of poor performance could be due to a poor contact between the cathode and its current collector because the current collector separated from the cathode and, when placed back on, may not have exactly fit into its original footprint. The cell was terminated after 504 hours of operation. The porous components were well bonded together but the cathode current collector was only partially attached to the cathode, verifying our early hypothesis. The carbonate inventory showed normal distribution of carbonate among porous components and no carbonate loss was accounted for with this short term cell.

Strengthened Anode Fabrication

No work was performed this quarter.

Cathode Dissolution

In 1996, we will continue to update in-cell cathode dissolution data by analyzing post cell test components. In 1996, four cells with Li/Na electrolyte have been terminated and analyzed for cathode dissolution. They are PDI-1, PDI-2, BS-TC-42-95-5, and BS-TC-66-93-4.

Their results were compared with the previously available cathode dissolution data. Briefly, the amount of nickel transported to the matrix is lowest for the Li/Na electrolyte with an unstabilized cathode. With stabilized cathodes, the Ni in the matrix with Li/Na is comparable to that of Li/K. A possible explanation could be that the electrolyte of Li/Na containing a cathode stabilizing agent which is the most basic among all IGT used electrolytes, has, in effect, enhanced the basic dissolution reactions for the cathode. We will, therefore, be operating Li/Na cells with unstabilized cathodes.

Alternate Cell Package Development

Extending the anode to the outside edge of the wet seal and to the inside edge of the oxidant manifold requires that the exposed edge of the anode be rendered electrochemically inert to prevent the formation of parasitic cells in those areas. These parasitic cells will decrease the cell OCV. The feasibility of rendering the parasitic cells inactive can be tested economically using 3 cm² cells as a screening tool. An anode treated to make it inert when exposed to the oxidant, can be used as cathode in a standard 3 cm² cell assembly. For the approach to work, the 3 cm² cell must show a very high cathode polarization, a very high cathode resistance, or both, are high enough, very little current in an actual cell will be very low or negligible, and the type of anode and its protection will work well extended to the outer edge of the cell. Two experiments were conducted to test the validity of this approach during this quarter.

Attempts were made to sinter Ni-3Al anodes under a wet N₂ atmosphere in large enough sizes to use in our 6 x 6 two-cell stack but the electrodes were weak and broke easily. Large anodes were made by sintering the Ni-3 Al tape under a dry N₂ atmosphere at 1100°C. Screening test SPM-T90 3 cm² was assembled with this electrode after which it was testing in a two-cell stack.

Cell SPM-T90 (3 cm²) was started during January as a screening test for the Ni-3Al anode. The cathode is the same Ni-3Al electrode used in the anode but was coated on both faces. The cell was expected to show a very poor cathode performance. After 72 hours of operation, the test was stopped. The cell was showing 2 mA/cm² at the normal operating cell potential and the cell resistance was estimated to be 24 ohms, or approximately 185 times the normal resistance. This indicates that in a 6 x 6 two-cell stack test the short circuit current should be negligible.

However, when a 6 x 6 two-cell stack was tested, (Cell IGT-BS-TC-42-96-1), the cells showed 29 and 35 mV lower OCV than expected. This is equivalent to a parasitic current of approximately 30 mA/cm². The N₂ crossover was 1.6 to 2.6%, and deteriorated with time. The relatively large N₂ crossover seems to indicate that leaking possibly was one of the causes of high parasitic current. If the anode was not properly sealed, leaks would increase the availability of CO₂ and O₂ around the outside edge and manifold areas, which would decrease OCV as well as increase the parasitic current. On termination, however, it was found that, because of oxidation, the anode had swelled around the outside edge of the cell and inside areas around the oxidant manifold and caused shorting of the anode and cathode flanges. To remedy this problem, the anode must be cut under-size around the outside edge and around the manifold areas and a gasket added to protect the edges and prevent deformation of the unsupported matrix portion on the edge and manifold.

Cell SPM-T91 was started with a Ni-5% Al₂O₃ green tape anode, and a Ni-5% Al₂O₃ green tape cathode on both faces, and a Li/K electrolyte. The cell was stopped after 144 hours of operation and was showing a negligible current density (2 mA/cm²) at the normal operating cell potential. The green tape anode thickness decreased by 40% and the porosity decreased by 20%. In contrast, the green tape Ni-5% Al₂O₃ cathode did not suffer any change in thickness. The large difference in the thickness change between the anode and the cathode indicates that the porosity of the green tape electrode is too high and larger cells will lose contact in the active area if the anode is extended to the edge because of sintering of the anode in the active area. Another test will be started with the same type of electrodes but either sintered or pressed to decrease porosity. If, as the 6 x 6 test seems

to indicate, sealing the anode shorting due to swelling of the anode around the outside edge and the tape manifold are the main problems when the anode is extended to the edge, a softer anode such as the green tape Ni+5% Al₂O₃ of cell SPM-T91, could help obtain good seals and prevent excessive swelling. The initial porosity of the tape, however, has to be low enough to prevent excessive sintering and shrinking in the active area.

Advanced Cell Package Fabrication

The functionality of out-of-cell preconditioned laminate consisting of cathode current collector, cathode and matrix was demonstrated by testing it in bench scale cell. The only other component provided to the cell was the anode and the anode current collector. The cell had a good OCV and wet seal efficiency and the gas crossover was low. The cell stabilized at a performance of 785-790 mV at 160 mA cm² without decay. Furthermore, it was thermally cycled to 100° C twice and it regained its performance level after each thermal cycle.

However, laminated components are not without problems. It must be extended to the edge and the electrode edges must be protected against opposing gases. Unless perfectly flat, it is susceptible to brittle fracture even under the weight of a 250-cell stack.

It has been decided that the conditioned laminate is not adaptable to the present stack hardware and the efforts should therefore be discontinued. M-C Power will continue to pursue lamination of green components to reduce manufacturing and handling cost.

Decrease Cathode Tortuosity

Computer modeling was used to study the effects of the BET surface area, thickness, electrolyte filling, and tortuosity on the performance of the cathode. The results indicated that two ways to improve cathode performance would be to increase the surface area used for the electrochemical reaction and to decrease cathode tortuosity. For this purpose we are attempting to align the cathode pores perpendicular to the electrode. This will decrease tortuosity by shortening the path length for the ionic and electrical currents moving through the electrode and will shorten the path length for the oxidant gases entering the electrode as well. The result should be a substantial decrease in ohmic resistance and a slight decrease in mass transfer polarization.

Cell 4-MOLS. This cell was started with a cathode made with aligned pores. The anode was Ni10Cr and the electrolyte was Li/K. The cell has operated 1,728 hours and shows a steady state cell potential of 915 mV at 160 mA/cm² with 35 and 56 mV anode and cathode polarizations respectively. The IR-drop of this cell is only 51 mV. At the lowest point, the IR-drop of cell 4-MOLS was 45 mV. As a comparison, the IR-drop of previously operated cell SPM-T89, which was very low because of the excellent conductivity of its Li/Na electrolyte, was 40 mV at steady state and currently operating cell SPM-T92, which also has a Li/Na electrolyte, currently shows 39 mV. The cell potential dropped 5 mV due to a facility wide power failure at 960 hours of operation.

Thin Anodes

The purpose of this work is to minimize the amount of nickel and the sintering inhibitor, chromium or aluminum, used to fabricate the anode by decreasing the thickness of the anode without impacting cell performance. This approach should translate into saving not only in nickel, sintering inhibitor, and tape casting materials but also in processing costs since the anode is used in a green state and does not require sintering. The use of a thin

anode also has the advantage of decreasing the height of the stack and lowering the mass.

Cell 5-PALS demonstrated that achieving and maintaining high cell potential is possible with thin reinforced anodes. However, a slight deformation of the anode and reinforcing was observed.

Cell 6-PALS was started during January with a painted Ni-3Al reinforced anode. The cell has a Ni-255 cathode and Li/K electrolyte. This cell reached 875 to 880 mV cell potential at 160 mA/cm² with approximately 50 mV anode polarization 65 to 70 cathode polarization and 55 to 60 mV IR-drop. The anode and cathode polarization are both on the high side. When a heavy discharge was performed after 768 hours of operation on Cell 6-PALS, to diagnose the cause of the high anode polarization, within minutes after the discharge, the anode polarization was down to 29 mV and the cell potential had improved to 901 mV up from 879 mV, but 24 hours later, the anode polarization was back up to 47 mV and the cell potential was down to 882 mV. This indicated that the anode reaction area increased due to the discharge, which might be fixed by decreasing the particle size of the Ni-3Al alloy powder. The high cathode polarization indicated poor matching. The cathode was depolarized at 864 hours of operation. The depolarization process brought the cathode polarization down from 70 mV to 34 mV and the cell potential improved to 918 mV from 880 mV.

Cell 6-PALS was terminated after 2,016 hours operation. At termination, the cell was showing 915 mV cell potential at 160 mA/cm² with 39 mV anode polarization, 36 mV cathode polarization, and 63 mV IR-drop.

Cathode Depolarization

Work performed in September (1995) led to the discovery of a method for substantially lowering cathode polarization. Several cells with Li/K electrolytes have been depolarized in this manner and results indicate that the cathode performance improves substantially as the result of a drop in cathode polarization and stable performance after the cathode was subjected to the depolarizing process.

The changes in cell performance with temperatures before and after the depolarizing process in a cell with Li/K electrolyte were studied in Cell SPM-T86. The results in this cell indicated that the depolarizing process substantially lowers cathode polarization and that the cell becomes less sensitive to changes in the operating temperature. Large gains in cell potential are seen. During January we started cell SPM-T89 with Li/Na electrolyte, a stabilized cathode, and a Ni-3Cr anode. The purpose was to study the depolarization process in a cell with Li/Na electrolyte. The results are discussed below.

Cell SPM-T89. At steady state the cell potential was 927 mV at 160 mA/cm². The anode polarization, at 44 mV, is slightly above the 35 to 40 mV normally observed and the cathode polarization, at 45 mV, is normal. However, the IR-drop, at 40 mV, is much lower than the 55 to 60 mV observed in cells with Li/K electrolyte and the performance is above the average of approximately 900 to 910 mV obtained with that electrolyte. We should point out that anode polarization as low as 25 mV has been obtained; therefore, with better anode selection, approximately 15 mV gain in cell performance with the Li/Na electrolyte can be realized.

The cell performance as a function of the temperature between 575° C and 675° C at 25° C

increments, prior to the depolarization process, was obtained after the cell reached steady state at 288 hours of operation. The cell was then subjected to the cathode depolarizing process. The cell was then allowed to recover from the depolarization process for 24 hours before obtaining again the cell performance as a function of temperature. After the depolarizing process, Cell SPM-T89 showed a steady state potential of 939 mV and the cathode polarization was 9 mV lower than what it was before the depolarizing process. The test was terminated after 700 hours of operation.

The results of the depolarization process in cell SPM-T89 with the Li/Na electrolyte, were compared to the results previously obtained in cell SPM-T89 with the Li/K electrolyte. Cell SPM-T89, with the Li/Na electrolyte, is more sensitive to changes in temperature than Cell SPM-T86 with the Li/K electrolyte, particularly at temperatures lower than approximately 600° C. Although the cell potential shows a small 8 to 10 mV improvement at 650° C after the depolarization process, the cell became even more sensitive to changes in the operating temperature and shows losses after the depolarization if the temperature is lower than approximately 615° C to 620° C. The cell potential at 575° C in the cell with Li/Na which was 768 mV before the depolarization became 759 mV after. By contrast, the cell potential at 575° C with the Li/K was 816 mV before the depolarization and improved to 894 mV after. Both the anode and the cathode polarization of the cell with the Li/Na electrolyte show steeper changes with temperature than the cell with Li/K; particularly, the cathode polarization shows a much faster increase below approximately 600° C.

By contrast, the anode and cathode polarization of the cell with the Li/K electrolyte are much less sensitive to changes in the operating temperature after depolarization, particularly the anode polarization shows very little or no change with temperature. The IR-drop of the cell with Li/Na electrolyte also shows a faster increase as the temperature is decreased than the cell with Li/K. However, while the cathode of the cell with the Li/Na electrolyte shows no sensitivity to changes in temperature and the cathode IR-drop shows a much larger change. The changes measured at 240 mA/cm² in the cell with Li/Na electrolyte were greater and the cell showed even more sensitivity to changes in the operating temperature. While after the depolarization process the cell potential at 240 mA/cm² was very low, unstable, the cell could not hold the load and the cell potential was dropping slowly with time.

The results indicate that the cathode depolarizing process results in 8 to 10 mV gain in cell performance due to lower cathode polarization, only if the temperature is 650° C or higher. However, losses in cell potential are seen when the temperature is below approximately 615° to 620° C, because the cell is much more sensitive to the operating temperature. The high sensitivity of the cell performance with the Li/Na electrolyte as the operating temperature is lowered was also seen in bench scale cells. The results suggest that a stack with a Li/Na electrolyte, a Ni-3Cr anode and stabilized cathode operating at 650° C average temperature would have a much lower output in cooler areas of the stack, particularly where the temperature is below approximately 600° C, than would a stack using Li/K electrolyte.

Since the cathode stabilizing agent dissolved in the electrolyte may be affecting the cell sensitivity to temperature, Cell SPM-T92 was started during March with similar components to those of SPM-T89 but without the stabilizing agent in the cathode, to study the effect of the stabilizing agent on the cell sensitivity to temperature. Another cell is being planned with a Li/Na/K ternary eutectic electrolyte, with melting point of 397° C, to

study the effect of the depolarization process in a cell with a ternary eutectic electrolyte.

Cell SPM-T92. This cell was started during March with a Ni-3Cr anode, a Ni cathode, and Li/Na electrolyte. After 288 hours of operation, the cell had reached a steady state potential of 910 mV, with 35 mV anode polarization, 67 mV cathode polarization, and 40 mV IR-drop. At this point, the temperature was lowered to 575° C and polarization curves were generated between 575° C and 675° C in 25° Increments with one additional at 588° C. The cell was depolarized after generating these polarization curves and currently we are generating the same polarization curves after the depolarization process. Early results show that at 650° C, the cell potential improves 31 mV at 160 mA/cm² and 49 mV at 240 mA/cm² after the cell is depolarized. At 575° C, the cell potential improves 75 mV at 160 mA/cm² and 107 mV at 240 mA/cm² after the cell is depolarized. These results are comparable to the results reported earlier for the Li/K electrolyte, where at 650° C, the cell potential improved 24 mV at 160 mA/cm² and 41 mV at 240 mA/cm² after the cell was depolarized. At 575° C, the cell potential improved 78 mV at 160 mA/cm² and 105 mV at 240 mA/cm² after the cell was depolarized. Evaluation of this cell is continuing, but preliminary results indicate that it is the stabilizing agent which interferes with the depolarization process when Li/Na is used.

Analytical Results for Cell SPM-T85

During the quarter the analytical results of cell SPM-T85 were received. Cell SPM-T85 had a Li/K electrolyte, was operated 2,000 hours and was depolarized. The results indicated that lithium content of the cathode is 4.64 atom %. Previous results for cells with Li/K electrolyte which have not been depolarized have shown the lithium content of the cathode to be 2.5 to 3.0 atom %. The high Li content of the depolarized cathode could be improving its catalytic properties and might be the reason for the excellent performance of the cathode after its depolarized. Two more samples of cathode from cells operated with 70 mole % Li₂Co₃/30 mole % K₂CO₃ have been submitted for analyses of lithiation to confirm the results. The cathodes of one of the cells was depolarized and other was not. The analysis of the matrix of Cell SPM-T85 indicated a nickel content of approximately 9.3 mg/cm², which is within what would be expected for a cell operated at 2,000 hours with a non-stabilized cathode, and indicate that the depolarizing process does not influence the solubility of the nickel in the Li/K electrolyte.

Bench Scale Testing

An overall summary of the cell tests conducted to date in this task is presented in Table 6.1.1.4.1. The performance of the cells that are in operation is summarized in Table 6.1.1.4.2.

CELL IGT-BS-TC-42-96-1

Cell IGT-BS-TC-42-96-1 was started effect of the opposing gas on the exposed anode in the oxidant manifolds and to evaluate a technique for protection of the anode from the oxidant gas. In this two cell stack test only the anode was extended to the edge and all other components (i.e. cathode, anode, and cathode current collectors) were housed inside the cell.

The test results of Cell IGT-BS-TC-42-96-1 indicated that the initial OCVs for the stack, Cell 1 (bottom), and Cell 2 (top) were within 62 mV, 29 mV, and 35 mV of the theoretical values of 2086 mV and 1043 mV, respectively. Thereafter, the OCV and performance of

the stack, Cell 1, and Cell 2 gradually decreased with time. GC analyses obtained on the fuel outlet at OC confirmed the existence of parasitic currents which increased in magnitude from 26 to 36 mA/cm² up to 120 hours of cell operation. The drop in OCV and performance was due to the existence of the parasitic currents between the cell active area, gas manifolds, and the peripheral edges.

It was thought that these parasitic currents are caused by the incomplete oxidation of the Ni-Al anodes in the peripheral edges so an oxidation test was conducted at 127 hours of cell operation. Before the test, the stack OCV was 1968 mV. After the test the stack OCV dropped to 1500 mV and reached a steady value of only 1579 mV. Also, the magnitude of the internal parasitic currents increased significantly from 36 to 122 mA/cm². In view of the OCV and performance decay, Cell IGT-BS-TC-42-96-1 was terminated after 288 hours of operation. Cell IGT-BS-TC-42-96-1 did not confirm the 3 cm² test results and the performance data of the cell test revealed that the edge protection did not effectively protect the anode edges and alternatives have to be found.

Post-test disassembly revealed that the exposed edges of the anode grew outward and salt squeezed out of these edges. This occurred in spite of the fact that the edges of the anode were also protected. The matrix in the active area was reddish and looked fully dense. The matrix in the wet seal area, however, was white and looked porous. The anode was badly oxidized at the wet seal area and the oxidized region had spread into the active area.

**Table 6.1.1.4.1. OVERALL SUMMARY OF BENCH-SCALE CELL TESTS
 CONDUCTED TO DATE IN TASK 6.1.1.4.**

Cell No.	Purpose	Status	Hours of Operati on	Conclusion
IGT-BS-TC-66-93-4	Determine cell performance by substituting the SOA Li/K electrolyte with Li/NA electrolyte at ambient pressure using reference gasses.	Terminated	16850	Longest operating Li/Na cell ever operated at the continuous load of 160 mA/cm ² . Demonstrated excellent endurance.
IGT-BS-TC-66-94-1	Determine performance characteristics of Li/Na electrolyte at system conditions.	Terminated	6908	No evidence of Ni-shorting.
CVC-BS-TC-94-1	Evaluate the performance of an out-of-cell preconditioned cell package.	Terminated	762	Successful demonstration of the out-of-cell preconditioned laminated cell package concept.
CVC-BS-TC-94-6	Same as for Cell CVC-BS-TC-94-1	Terminated	1558	Cell did not perform well due to high IR. Warpage is a problem with the second version laminate using a sintered cathode.
IGT-BS-TC-42-95-2	To test electrodes to edge and determine effects of opposing gas on the electrodes in the manifold areas.	Terminated	189	Results confirm that the edges of the electrodes have to be protected.
IGT-BS-TC-42-95-3	To test electrodes to edge and determine the effects of opposing gas on the electrodes in the manifold areas.	Terminated	187	Re-evaluate the method of electrode ege protection.
IGT-BS-TC-42-95-1	Evaluate the performance of a pre-conditioned laminate with Li/Na electrolyte.	Terminated	2161	Successful demonstration of the laminate with Li/Na electrolyte
MCP-IM9501	Evaluate the operating characteristics of a matrix cast without pre-wetting with carbonate	Terminated	266	Poor cell performance due to electrode switch during assembly.
MCP-IM9505	To determine the performance of a cell package taken from the active area of the 250 cell stack.	Terminated	187	Cell did not perform well due to high IR.
MCP-IM9506	To determine the performance of a thinner cell package using a stabilized cathode and a li/Na electrolyte. The anode and matrix thickness are half that currently used.	Terminated	72	Cell terminated due to a low OCV of 790 mV.
IGT-BS-TC-42-95-4	To test electrodes to edge and determine effect of opposing gas on the electrodes.	Terminated	382	Re-evaluate the method of electrode edge protections.

**Table 6.1.1.4.1. OVERALL SUMMARY OF BENCH-SCALE CELL TESTS
 CONDUCTED TO DATE IN TASK 6.1.1.4.**

IGT-PDI-1	Determine performance characteristics of the Li/Na Electrolyte under system conditions.	Terminated	2352	Performance comparable to previously operated cells assembled with similar components.
IGT-PDI-2	Determine the cell performance having a cathode stabilizing added to the Li/Na electrolyte at 3 atm under system conditions.	Terminated	2352	Matching cell performance data is not available for a direct comparison.
IGT-BS-TC-42-95-5	Evaluate the performance of a preconditioned laminate with LiNa.	Terminated	504	Cell did not perform well due to high IR.
IGT-BS-TC-42-95-6	Determine the effect of opposing gas on the exposed cathode.	Terminated	309	Re-evaluate the method of electrode edge protections.
MCP-IM9502	To determine the performance of Ni+3Al anode operated at system conditions using Li/Na.	Terminated	1100	Cell did not perform well due to a high decay rate (55mV/1000 hrs.).
MCP-IM9503	To evaluate an alternative concept for electrolyte loading.	Terminated	2376	The cell performance is comparable to the SOA cells.
MCP-IM9504	To determine the endurance characteristics of the Li/Na electrolyte at 3 atm and under system conditions	Terminated	792	Cell test terminated due to poor performance.
IGT-BS-TC-42-96-1	Determine effect of opposing gas on the exposed anode in the oxidant manifolds.	Terminated	288	Re-evaluate the method of electrode edge protection.
IGT-PDI-5	Determine cell performance at 3 atm 250 mA/cm ² Li/Na electrolyte and Market Entry Oxidant (MEO)	Terminated	3480	Cell did not perform well due to carbonate losses
IGT-PDI-6	Determine cell performance at 700°C under pressurized operations (3 atm) with MEO	Terminated	2376	Severe corrosion of CCC and carbonate losses due to high operating temperature (700° C).

Table 6.1.1.4.2. PERFORMANCE SUMMARY OF THE BENCH-SCALE CELLS THAT ARE IN OPERATION								
Cell No.	Hrs. of Op.	OCV	Cell Data (mV)			Wet Seal Efficiency, %		N ₂ Crossover %
			Perform. *	IR*	Polarization*	Anode	Cathode	
IGT-PDI-5	1632	1054	740	65	249	97	100	0.6
IGT-PDI-6	480	1018	666	62	290	100	100	1.1
IGT-PDI-8	480	1019	659	100	260	100	97	0.9

* At a current density of 250 mA/cm².

+ Under system conditions, 75% U_iF and 40% U_iO.

+ At current density of 160 mA/cm² 60% U_iF, 40% U_iO and for the gas type SF/SO.

CELL IGT-BS-TC-42-96-2

Cell IGT-BS-TC-42-96-2 was assembled with an out-of-cell pre-continued cathode/matrix/carbonate/anode laminate and the cathode current collector both extended to the wet seal. The anode current collector was placed within the flange. The anode which was extended to the edge was protected around the perimeter. The purpose of this test is to evaluate the performance of the out-of-cell laminated cell package fabricated with the Li/Na electrolyte. The performance graph for Cell IGT-BS-TC-42-96-2 is shown in Figure 6.1.1.4.2.1.

The results indicated that the cell performance at 160 mA/cm² increased from 410 mV to 658 mV due to decrease in IR (220 mV) and polarization (28 mV). The cell could not be loaded to a current density of 160 mA/cm² until 168 hours of operation due to high IR. The cell resistance was initially high at 48 mohms and decreased to 9 mohms due to an incremental increase in holding force from 15 to 30 psi. The cell OCV of 1042 mV matched the theoretical value of 1043 mV. The anode and cathode wet seal efficiencies are 97% and 100%, respectively, and the nitrogen crossover is ~ 2.0%.

It is important to note that the cell attained the correct open circuit voltage with the anode extended to the edge indicating that no internal parasitic currents exist in the cell. This was confirmed by the GC analyses conducted on the fuel outlet at OCV conditions. These preliminary results suggest that the edge protection employed in this cell is capable of protecting the extended anode from the ambient air (oxidizing environment) surrounding the cell. In view of this, the protection technique will be evaluated for electrode edge protection in a 6 x 6 cell test. To date the cell has operated for 312 hours.

Figure 6.1.1.4.2.1
 Life Plot Of Cell IGT-BS-TC-42-96-2

CELL IGT-PDI-5

The purpose of this cell test is to establish the performance characteristics of a cell operating at 3 atm pressure and a current density of 250 mA/cm² with system fuel and a market entry oxidant (MEO) specified by M-C Power.

The cell performance under system conditions and 75% fuel utilization and 40% oxidant utilization as a function of time and pressure is shown in Figure 6.1.1.4.3.1. After stabilizing the cell at ambient conditions, the cell was pressurized to 3 atm at 504 hours of operation. The average cell potential at 250 mA/cm² and 3 atm pressure was about 740 mV with an OCV of 1050 mV (8 mV higher than the theoretical value of 1042 mV). The observed performance improvement of 53 mV when the pressure was increased from 1 to 3 atm is in good agreement with the 60 mV gain predicted by the PSI model. The cell performance remained stable at 740 mV for 1656 hours of pressurized operation (504 to 2160 hours).

The cell performance then decreased from 740 mV to 634 mV between hours 2184 through 3456 due to an increase in polarization. The cell experienced a precipitous drop in voltage (84 mV) between hours 3084 through 3456. The anode and cathode wet seal efficiencies were 93% and 100%, respectively, with a nitrogen gas crossover of 0.8%. Two decay rates were determined from the cell performance data shown in Figure 6.1.1.4.3.1 - a cell decay rate of ~8 mV/1000 hours from 504 to 3048 hours of operation and a decay rate of ~260 mV/1000 hours from 3120 to 3456 hours of operation. Carbonate loss could be the cause for this performance drop and high cell decay rate. In view of the high decay Cell IGT-PDI-5 was terminated after 3456 hours (2969 hours at 3 atm and 250 mA/cm²) of operation. For Cell IGT-PDI-5, all four sides of the flanges were aluminized. This probably resulted in carbonate loss due to creepage from the active area components. This test will therefore be repeated without aluminization exterior of the flange surfaces to demonstrate endurance.

Salt deposits were observed on the aluminized exterior surfaces of the anode flange of Cell IGT-PDI-5. After the cell was opened, it was observed that all components were bonded together and were stuck to the anode side hardware. There were corrosion flakes on both sides of the cathode current collector but the severity of flaking was not as severe as PDI-6. There were a few cracks that extended from the wet seal to the active area. The gas side of the anode current collector was stained suggesting partial oxidation of the anode side components.

Figure 6.1.1.4.3.1
Life Plot Of Cell IGT-PDI-5

CELL IGT-PDI-6

The purpose of this test is to determine the performance characteristics of a cell operating at 3 atm and a current density of 250 mA/cm² with system fuel and a market entry oxidant (MEO) specified by M-C Power.

The cell performance under system conditions and 75% fuel utilization and 40% of the oxidant utilization as a function of time and pressure is shown in Figure 6.1.1.4.3.2. The cell was pressurized to 3 atm after 625 hours of ambient operation. The average cell potential at a current density of 250 mA/cm² and at 3 atm pressure was about 734 mV. The average OCV of 1042 mV at 3 atm matched the theoretical value of 1041 mV very closely. The observed performance improvement of 66 mV when the pressure was increased from 1 to 3 atm is in close agreement with the 670 mV gain predicated by the PSI model.

After 792 hours of operation, the cell temperature was increased from 650° C to 700° C to determine the effect of 700° C operation, effect on performance and long term carbonate losses under system conditions. With an increase in cell temperature from 650° C to 700° C, the OCV, IR, and polarization decreased by 13 mV, 12 mV, and 12 mV, respectively while the cell potential increased from 734 to 745 mV (11 mV gain). The cell performance at 700° C, 3 atm, and 250 mA/cm² under system conditions decreased from 745 mV to 685 mV between 864 and 2352 hours of continuous operation at the above conditions. Also, the nitrogen gas crossover increased from 1.2 to 11%. The performance drop is attributed to the increase in the nitrogen gas crossover and carbonate losses resulting from the higher operating temperature of 700° C. The anode and cathode wet seal efficiencies were 97% and 100%, respectively. The overall cell decay rate was determined to be ~ 44 mV/1000 hours from 864 to 2352 hours of operation at 700° C and 3 atm. In view of the poor cell performance and to preserve the integrity of the post-test analysis results, Cell IGT-PDI-6 was terminated after 2352 hours (1560 hours of continuous operation at 3 atm, 250 mA/cm², and 700° C) of operation. Another bench-scale cell will be assembled and operated at 700° C to confirm and duplicate the results of cell test IGT-PDI-6.

Post-test disassembly showed that all components were bonded together and were stuck to the anode side hardware. There was a severe flaking of the cathode current collector and the gas channels of the cathode flange had rusty spots. There was a crack near one corner of the matrix running along the wet seal/active area transition region. There were also two cracks extending from the wet seal to the active area. When the bonded components were broken apart, the matrix cross section was crumbly and appeared porous or dry. The gas side of the anode was badly oxidized. The porous components will be analyzed for carbonate inventory to assess the effect of the 700° C operating temperature on carbonate losses.

Figure 6.1.1.4.3.2
 Life Plot Of Cell IGT-PDI-6

CELL IGT-PDI-8

The purpose of this cell test is to determine the performance characteristics of a cell operating at 3 atm pressure.

Operation of Cell IGT PDI-8 continued this quarter at 3 atm and 250 mA/cm². The cell performance as a function of time and pressure is shown in Figure 6.1.1.4.3.3. The data indicate that the cell potential at 3 atm and 250 mA/cm² is stable at 725 mV. The anode and cathode wet seal efficiencies are 87% and 100%, respectively, and the nitrogen crossover is ~ 2.6%. To date, the cell has operated for 2544 hours (1893 hours at 3 atm and 250 mA/cm²) and will continue its operation under system conditions.

For Cell IGT-PDI-8, a constant utilization polarization test was conducted to determine to cell power output as a function of current density. The power curve is shown in Figure 6.1.1.4.3.4. In this figure, for each current density the gas flows were set for 75% fuel utilization and 40% utilization at 3 atm pressure. The results in Figure 6.1.1.4.3.4 indicate that a) the power output from the cell at a current density of 350 mA/cm² (325 A/ft²) is ~ 309 W/ft² and b) the cell did not attain the maximum power density yet at 350 mA/cm².

Overall, the results from Cells PDI-5, 6, and 8 described above demonstrate the feasibility of continuous operation at 3 atm and a high current density of 250 mA/cm² under market entry stack conditions.

CELL IM9504

The purpose of the test was to determine the endurance characteristics of the Li/Na electrolyte at 3 atm and under system conditions. This test was a repeat of Cell IGT-BS-TC-66-94-1 operated for 7000 hours at 3 atm and under system conditions with Li/Na electrolyte.

The cell performance data as a function of time and pressure indicated that the cell performance at 160 mA/cm² decreased from 640 mV to 620 mV due to an increase in polarization. The average cell OCV at 1 atm was 996 mV, 6 mV higher than the theoretical value of 990 mV. The cell was then pressurized to 3 atm under system conditions with the gas type SF₆/SO and the performance at these conditions and 160 mA/cm² (75% U_F and 40% U_O) was about 700 mV. This performance was ~ 60 mV lower than that obtained for Cell IGT-BS-TC-66-94-1 under similar conditions. The average OCV of 1012 mV at 3 atm was 4 mV higher than the theoretical value of 1008 mV under system conditions. The cell performance at 3 atm and 160 mA/cm² then slowly decreased from 700 mV to 692 mV due to an increase in polarization. The anode and cathode wet seal efficiencies were 98% and 99%, respectively, and the nitrogen gas crossover was low at 0.2%. In view of the poor performance, Cell IM9504 was terminated after 792 hours of operation.

Figure 6.1.1.4.3.3
 Life Plot Of Cell IGT-PDI-8

Figure 6.1.1.4.3.4
Power Output As A Function Of Current Density For Cell IGT-PDI-8
(At 3 atm Pressure, 75% U_F and 40% U_O)

CELL IM9601

The purpose of this test is to determine the baseline performance and endurance for a Ni+1Al anode and a stabilized Ni cathode operated at 3 atm pressure with system gases (gas type SF/SO) using the Li/Na electrolyte. This test is a repeat of Cell IM9502 operated at ~ 740 hours at 3 atm and 160 mA/cm² under system conditions with Li/Na electrolyte.

The cell performance as a function of gas type (SF/RO and SF/SO) and time is shown in Figure 6.1.1.4.1.1. The cell was set to operate at 60% fuel utilization and 50% oxidant utilization for the gas type SF/RO and for the gas type SF/SO at 60% fuel utilization and 40% oxidant utilization at 160 mA/cm².

The data indicate that the cell performance at 160 mA/cm² and 1 atm increased from 642 mV to 758 mV due to decreases in IR (4 mV) and polarization (12 mV) while operating under the SF/RO conditions. This performance of 758 mV is ~ 20 mV lower than that obtained for Cell IM9502 under similar conditions. The average OCV of the cell was 1051 mV which is 3 mV lower than the theoretical value of 1054 mV.

The gases were then switched to system fuel and system oxidant (SF/SO) at 1 atmosphere. The cell performance under system conditions at 160 mA/cm² was ~ 711 mV. This performance is ~ 8 mV lower than that obtained for Cell IM9502 under similar conditions. The average OCV of the cell was 1001 mV, which is 11 mV higher than the theoretical OCV value of 990 mV at 1 atmosphere. The anode and cathode wet seal efficiencies were 97% and 100%, respectively, with a nitrogen crossover of 2.0%. The cell performance at 1 atm and at 160 mA/cm², 75% U_F, and 40% U_O was ~ 745 mV for gas type SF/RO and about 692 mV for the gas type SF/SO. To date, Cell IM9601 operated for 504 hours and will be pressurized to 3 atm next month.

Figure 6.1.1.4.4.1
 Life Plot of Cell IM9601

Subtask 6.2 Fuel Cell Module

Objective: The performance and cost of the fuel cell module hardware is critical for a market entry product. Scaling-up from commercial area short stack hardware to a commercial unit will be accomplished in this task. Both analytical modeling, including finite element analysis, and full scale hardware testing will be used in this process.

Status: Inactive during this reporting period.

Subtask 6.3 Balance of Plant Component Development

Objective: In this task, Bechtel's second year activities are as following:

- Screen and select the major BOP component developers
- Define the overall development program, scope of work, and budget with each developer
- Conduct contract negotiation with each developer

- Coordinate the technical support from the developers for the trade-off studies and the preliminary design and cost estimate in Task 2

In the second year, the effort described above will be carried out for the power conditioner, reformer with catalytic combustor, turbo machinery and the HRSG unit, which are all BOP components.

Status: *Bechtel has been contacting and working with several vendors on this subtask.*

Subtask 6.4 Full-Area Stack Tests

Objective: Commercial-area stack tests are used to verify improvements in the design, fabrication, and performance of full-area components and processes and to verify operational advancements in the technology.

Status: Fabricate and Operate 20kW Non Pressurized Stacks
Inactive during this reporting period.

Stack Failure Mode Verification
Inactive during this reporting period.

Subtask 6.5 MW-Class Power Plant Demonstration

Objective: The major purpose of this demonstration unit is to verify commercial readiness of M-C Power's IMHEX® fuel cell power plant by demonstrating the characteristics, performance, and operability of a prototype market-entry unit at a customer site.

Status: *Inactive during this reporting period.*

Subtask 6.6 Update Commercialization Plan

Objective: The commercialization plan will be updated based on the results of the MW-class demonstration.

Status: *Inactive during this reporting period.*

APPENDIX A: ISO 9001 Quality Assurance Procedures

1	<u>Management Responsibility</u>		Performance Testing Requirements
	Quality Policy Maintenance		Inspection and Test Records
	Responsibilities for Quality	11	<u>Inspection, Measuring, and Test Equipment</u>
	Quality Program Management		Approved Gauge Specifications
2	<u>Quality System</u>		Gauge Calibration and Certification
	Performance of Quality System Reviews	12	<u>Inspection and Test Status</u>
	Quality System Documentation Requirements		Inspection and Test Status
	Development of Quality Plans		Indication of Test Status
3	<u>Contract Review</u>		Product Release Status
	Performance of Contract Reviews	13	<u>Control of Nonconforming Product</u>
4	<u>Design Control</u>		Control of Nonconforming Material
	Identification of Developmental Issues		Review & Disposition of Nonconforming Material
	Design Release Status		Request for Deviation or Waiver
	Planning of Design and Development Activities		Rework Material
	Technical Interfaces for Design Reviews		Request for Material Review
	Development of Design Input Requirements		Conditional Release of Nonconforming Product
	Development of Design Output Requirements		Rework of Nonconforming Product
	Performance of Design Reviews		Product Recall
	Design Verification	14	<u>Corrective Action</u>
	Design Validation		Requests for Corrective Actions
	Control of Design Changes		Investigation of Nonconformances
5	<u>Document Control</u>		Corrective Action Implementation and Review
	Requirements for Controlled Documents		Supplier Corrective Actions
	Quality Manual Maintenance		Preventative Action Requirements
	Quality Procedure Development & Approval	15	<u>Handling, Storage, Packaging, and Delivery</u>
	Operating Procedure Development & Approval		Specification of Handling & Storage Requirements
	Drawing Approval		Development of Handling and Storage Procedures
6	<u>Purchasing</u>		Storage of Perishable Materials
	Quality Specifications for Purchased Products		Special Handling Requirements
	Vendor Certification and Selection	16	<u>Quality Records</u>
	Assessment of Subcontractors		Required Quality Records
	Verification of Purchased Product		Quality Record Maintenance and Retention
	Vendor Product Certification	17	<u>Internal Quality Audits</u>
8	<u>Product Identification and Traceability</u>		Internal Quality Audit Preparation and Planning
	Material Identification		Internal Quality Audit Performance
	Material and Component Traceability		Internal Quality Audit Reporting
	Material Transfer		Internal Quality Audit Corrective Action & Review
9	<u>Process Control</u>	18	<u>Training</u>
	Process Development & Capability Assessment		Employee Orientation
	Process Control Requirements		Requirements for Quality Training
	Certification of Manufacturing Processes		Requirements for Technical Training
	Temporary Process Deviations		Certification Requirements
	Production Hold	19	<u>Servicing</u>
	Experimental/Developmental Processes	20	<u>Statistical Techniques</u>
10	<u>Inspection and Testing</u>		Application of Statistical Techniques
	Incoming Material Inspection and Testing		Test Method Certification
	Measurement Terminology		Data Assessment and Control
	Measurement Test Units		Development of Sampling Plans
	Acceptance Sampling & Material Certification		Use of Control Charts
	In-process Inspection and Testing		
	Final Inspection and Testing		
	Requirements for Lot Certifications		

APPENDIX B: QA and Analytical Procedures

Test and Measurement Procedures

Main Rail Measurements
Separator Plate Rib Measurements
Separator Plate Dimple Measurements
Separator Plate Flatness Measurements
Bipolar Plate Total Wet Seal Measurements
Tapped Hole Qualification
Bipolar Plate & Half Cell Visual Inspection
Modified Total Wet Seal Measurements
Nickel Testing
Bipolar Plate Total Step
Dimple Amplitude Measurements
Feed Channel Measurements
Rib Amplitude Measurements
CMM Program List
CMM Data Transfer / Conversion
CMM Start-Up
CMM Preventive Maintenance
CMM Probe Tip Calibration
CMM Main Rail Measurements
CMM Bipolar Plate Measurements
CMM Bipolar Plate Rail Profile Measurements
CMM Bipolar Plate Planform Measurement
Electrode Data Conversion Procedure
CMM Text File Conversion Procedure

QA Laboratory Operating Procedures

Microscope Reticle Measurement
Grinding of Stainless Steel Plate Samples
Sample Preparation of Anode XRD Sample
Preparing a 3" Cold Mount
Carbonate Apparatus
Electrode Carbonate Washing
Microwave Digestion
Mercury Porosimetry
Cold Mounting of Anode XRD Sample
Tape Caster Waste Water Analysis
Grinding of Stainless Steel Plate Samples
Preparing a Hot Mount

Stack Gas Analytical System Operating Procedures

System Layout
System Flow Schematics
Independent System Operation
Operating Program Overview
Data Transmission Schematic
Chromatograph Manual Operation
Chromatograph Supplemental Ports
Dew point Analyzer Strip Chart
Dew Point Digital Output
Initiating Operating Program
Initiating Send report Option
Chromatograph Start-Up Procedure
Chromatograph Calibration

Chromatograph Support Gases
Total Hydrocarbon Analyzer Start-Up Procedure
Total Hydrocarbon Analyzer Calibration
Total Hydrocarbon Analyzer Support Gases
Chromatograph Integrator Start-Up
Resetting Integrator
Integrator Input Level Adjustment
Integrator Threshold Evaluation
Analytical System Start-Up
Analytical System Shut-Down
Desiccant Cartridge Replacement
Balancing Dew Point Sensor Optics
System Leak Check
Support Gas Cylinder Replacement

Description of Attachments

★ U.S. Department of Energy, Morgantown Energy Technology Center, Contract Report Transmittal Checklist

T. G. Benjamin, PDI Project Manager - Date

DOE Reviewing Representative

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.