Molten Carbonate Fuel Cell Product Design & Improvement - 3rd Quarter, 1995

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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 (7/1/95 - 9/30/95)

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.

Subtask 1.1.1 Market Surveys

Objective: Bechtel will assist M-C Power to conduct a market survey. In this survey, potential users of the fuel cell unit in different business segments and different regions will be contacted to obtain pertinent information about current utility usage, needs and costs.

Status: *M-C Power is developing a preliminary market survey, which will be issued to a variety of potential customers.*

Subtask 1.1.2 Analyze Market Surveys, Codes and Regulations

Objective: Bechtel will assist M-C Power to analyze the data collected in Task 1.1.1 to identify the business segments and regions which have the highest market potential and to estimate this potential market size.

Status: *This task is dependent on the completion of task 1.1.1 above.*

Subtask 1.1.3 Generate Product Requirements Document

Objective: Bechtel will assist M-C Power to summarize the analysis conducted in tasks 1.1.1 and 1.1.2 into a cohesive document. A final document will be issued by incorporating the comments received.

Status: *This task is dependent on the completion of tasks 1.1.1 and 1.1.2 above.*

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.

Subtask 1.2.1 Product Options

Objective: For the fuel cell unit to be a viable commercial product for on-site and distributed power generation, it has to compete with purchased power from grid, reciprocal engines and small gas turbines. Bechtel will determine the acceptable cost range for the fuel cell unit by conducting an economic comparison with the competing power supply and generation options.

Status: *Bechtel is currently conducting a product option trade-off study for this task. Bechtel will issue a report summarizing Bechtel's results on these studies. The final product definition is also dependent on the results of subtask 1.1.*

Subtask 1.2.2 Product Option

Objective: Based on the market analysis done in task 1.2.1, Bechtel will define the commercial unit in terms of the following items:

- Power generation capacity of the unit
- Desired steam, hot water and hot gas production rates and delivery pressures and temperatures
- Acceptable thermal efficiencies
- Acceptable capacity rating with ambient temperature
- Acceptable turndown ratio
- Acceptable load following capability
- Minimum thermal cycling capability
- Minimum availability required for the unit
- Noise and emission limits
- Applicable codes and standards
- Maximum plot area allowed
- Acceptable cost range of the unit

Bechtel will issue a report which summarizes the economic comparison conducted in task 1.2.1 and the product definition in task 1.2.2.

Status: *Depends on the results of subtask 1.2.1.*

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.

Subtask 1.4.7 Product Environmental Plan

Objective: Environmental compliance regulations of representative locations within the U.S.A. regarding the operation of IMHEX® fuel cell power plants and their fabrication and decommissioning will be assessed. A plan will be developed to address requirements of the conceptual manufacturing facility, including the recycling of decommissioned stacks and expended components.

Status: *The NEPA report has been submitted by M-C Power. This subtask is complete.*

Subtask 1.4.9 Product Cost Reduction Plan

Objective: M-C Power will develop a cost reduction cost benefit analysis showing the steps required to achieve user performance and cost requirements.

Status: *Depends on the findings of the market survey that will be done in subtask 1.1.1.*

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 System Optimization

Subtask 2.1.1 Power Plant Baseline Design

Objective: Bechtel will use the design and cost estimate in a recently completed GRI fuel cell balance of plant (BOP) cost analysis study as the baseline system against which trade-off studies will be performed.

Status: *Trade-Off studies are in progress.*

Subtask 2.1.2 Power Plant Performance Trade-Off Studies

Objective: Bechtel will perform several trade-off studies to determine the optimum operating parameters and process configuration for the commercial unit. A single variable will be changed at a time to identify its impacts on the plant performance and cost. Any efficiency improvement will be weighed against the increase in plant complexity, cost and physical dimensions. The trade-off studies to be conducted are listed below:

- ▶ Current Density Optimization

- ▶ Pressure Optimization
- Optimum Combustion Temperature in the Reformer
- ▶ Adding Shift Catalyst to the Reformer

Status: *M-C Power is currently working with Bechtel to provide input for these trade-off studies.,*

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.

Subtask 2.2.1 **Power Plant Process Design**

Objective: In this task, Bechtel will first prepare a detailed process flow diagram and develop the heat and material balance over a wide range of operation including the normal operation, startup, and shutdown.

Bechtel will then size the equipment, including those items required for startup and shutdown. The equipment specification will contain sufficient details for suppliers to estimate the costs and develop preliminary sketches of the equipment dimensions.

Status: *M-C Power is currently working with Bechtel to provide input for the power plant design work.*

Subtask 2.2.2 **Power Plant System Engineering**

Objective: In this task, Bechtel, with support from Stewart & Stevenson (or others), will specify the piping, valves, insulation, structural steel, instruments, control, and electrical requirements for the commercial unit. Bechtel and Stewart & Stevenson will also develop a layout.

Status: *No significant progress to report on this subtask during the current reporting period.*

Subtask 2.3 **Generate Preliminary Cost Estimate**

Subtask 2.3.1 **Power Plant Capital Cost Estimate**

Objective: In this task, Bechtel will prepare jointly with Stewart & Stevenson (or others), a capital cost estimate for the commercial unit.

Status: *No significant progress to report on this subtask during the current reporting period.*

Subtask 2.3.2 **Power Plant Operating Cost Estimate**

Objective: Bechtel will, jointly with M-C Power, estimate the operating labor and establish the maintenance schedule, labor, and materials requirements for the commercial unit. The maintenance requirements will be extrapolated from plants with similar service severity and operating environment. The chemicals and catalysts consumption will be calculated. M-C

Power will project the cell life as to determine the stack replacement cost.

Status: *No significant progress to report on this subtask during the current reporting period.*

Subtask 2.3.3 Power Plant Economic Analysis

Objective: Based on the capital and operating costs developed, Bechtel will conduct an economic analysis to determine the cost of electricity. This analysis will follow the methodology established in EPRI's Technical Assessment Guide (TAG).

Status: *Depends on the completion of subtasks 2.3.1 and 2.3.2.*

Subtask 2.4 Performance Analysis

Subtask 2.4.1 Power Plant Design Performance

Objective: Based on the design conducted in subtask 2.2, Bechtel will calculate and summarize the plant performance of the market entry unit at the rated capacity.

Status: *Depends on the completion of subtask 2.2.*

Subtask 2.4.2 Power Plant Off-Design Performance

Objective: The off-design performance to be evaluated for the market entry unit include:

- ▶ The minimum turndown ratio
- ▶ Part load efficiency
- ▶ Capacity rating as a function of ambient temperature

Status: *Depends on the completion of subtask 2.2.*

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.

Subtask 3.1.1 Computerized Cell Component Manufacturing Process Simulation

Objective: Discreet system simulation programs and analytical modeling programs for the evaluation of statistical variability within the linked manufacturing processes will be evaluated. When this information is combined with the normal manufacturing process routings, the analysis

will project manufacturing throughput and will allow for the study of capacity and labor costs in a realistic environment.

Capital equipment utilization will be examined to determine the effect on product cost and quantity. These studies will lead to a definition of future equipment and staffing needs and provide a basis for a conceptual factory design.

Status: *M-C Power continues to develop a computerized process simulation that will be used to analyze the current manufacturing process as well as optimize this process. M-C Power is also investigating ways to automate the current manufacturing processes in order to reduce the overall cost per kW for the fuel cell stack.*

Subtask 3.1.2 Analyze Cell Component Manufacturing Process

Objective: The object of this task is to conduct a detailed evaluation of the current manufacturing processes so that areas for improvement can be selected and prioritized. Statistical methods will be used to determine key process parameters, to assess control philosophies, and to reduce active component variation. Design of Experiment Techniques and Statistical Process Control will be used as the basis for improving the manufacturing process.

Status: *M-C Power continues to develop a computerized process simulation that will be used to analyze the current manufacturing process as well as optimize this process. M-C Power is also investigating ways to automate the current manufacturing processes in order to reduce the overall cost per kW for the fuel cell stack.*

Subtask 3.1.3 Optimize Current Cell Component Manufacturing Process

Objective: Based on the analysis and simulation of Task 3.1.1 and 3.1.2, on-line control and process improvements will be selected which optimize yields while maximizing throughput without impacting quality. The optimization of the process will focus on problem definition and solving, evaluating options, statistical testing, updating control documentation, and selecting process improvements which can be implemented to enhance baseline production facilities without impacting delivery schedules or quality.

Status: *Depends on the completion of subtasks 3.1.1 and 3.1.2.*

Subtask 3.1.4 Automate Current Cell Component Manufacturing

Objective: Optimization and automation of the current manufacturing processes which improve cost, quality, production rate, and safety in active cell component production will be implemented. This includes decreasing direct labor costs, combining tasks, installing process instrumentation and controls, improving handling systems, and adopting on-line quality controls.

Status: *M-C Power is investigating ways to automate the current manufacturing processes in order to reduce the overall cost per kW for the fuel cell stack. The layout of some of the processes is being changed to facilitate the product flow through the furnace area.*

Subtask 3.1.5 Maintain Manufacturing Equipment

Objective: The manufacturing facility will be maintained according to a regularly scheduled maintenance program has been developed and will be followed to ensure proper and reliable operation.

Design, procurement, and refurbishing of the sintering furnace and other key manufacturing equipment will be accomplished under this task. Cost covers labor, services, materials and subcontractor labor.

Status: *M-C Power is working with the sintering furnace manufacturer and a local contractor to complete the sintering furnace upgrade. The furnace has been dismantled and all of the retrofit work is scheduled to be completed during the first quarter of 1995.*

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.

Subtask 3.2.1.1 Improved Plate Manufacturing Process

Objective: Advanced, cost-effective manufacturing processes for plate hardware to reduce cost and improve quality will be evaluated. Four steps have been identified: forming, trimming, joining, and aluminizing.

Status: *M-C Power is reviewing and investigating the four (4) steps listed above for alternate, more cost effective processes.*

Subtask 3.2.1.4 Verify Improved Plate Manufacturing Techniques

Objective: Plates and sections of plates will be tested in out-of-cell and in-cell tests to verify dimensional quality and operational performance. Improvements will be selected which can be implemented and will reduce fabrication cost.

Status: *Depends on the completion of subtask 3.2.1.1.*

Subtask 3.2.2 Implement Improved Plate Manufacturing Phase I Processes

Objective: Improved plate designs will be combined with selected advanced plate fabrication techniques and implemented in order to reduce costs. Successful evaluations of advanced plate processing techniques and material suppliers will result in a formal recommendation to adopt and implement these new process technologies or fabricators.

Status: *Depends on the findings found in subtask 3.2.1.1.*

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.

Subtask 3.3.1.1 Identify Advanced AC Candidate Manufacturing Processes

Objective: Processes will be identified and qualified at subscale levels for the rapid, low-cost fabrication of electrodes, electrolyte, matrix tapes, and separator plates. Advanced manufacturing techniques will be evaluated for achieving high-rate, durable manufacturing processes. The goal is to achieve an order of magnitude increase in throughput with no adverse impact on quality or performance.

Status: *Advanced manufacturing techniques are currently being investigated.*

Subtask 3.3.1.3 Procure Advanced AC Candidate Manufacturing Equipment - Phase I

Objective: After identification and evaluation of improved processes subscale equipment will be procured for verification trials. Evaluation and qualification of new equipment in these processes at sub-scale sizes will be conducted to verify process acceptability and cost-effectiveness prior to full scale implementation. A thorough costing analysis will be conducted prior to the adoption of advanced manufacturing processes to ensure the viability of the selected option.

Status: *Depends on the completion of subtask 3.3.1.1.*

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: *Depends on the completion of subtask 3.3.1.1.*

Subtask 3.4.2 Implement Advanced Manufacturing Process Scale Up Phase I

Objective: Full-scale equipment for advanced processes which can be cost-effectively scaled up and implemented into existing facilities will be procured and installed. Advanced equipment will be shaken down, tested, and used for component production to verify cost savings in low production volumes. Advanced component technologies developed under subtask 6.1 will be evaluated in commercial-scale stack hardware under this or parallel programs.

Status: *Depends on the completion of previous subtasks.*

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.

Subtask 3.5.2 Develop Advanced Plate Design

Objective: Advanced design and cell package concepts have the greatest potential for decreasing the cost of the IMHEX® stack. Modified and innovative plate concepts that illustrate the potential for order-of-magnitude cost reductions (such as one piece plate design) will be evaluated. Engineering drawings will be prepared and implemented in commercial-scale

hardware if appropriate. These concepts may first be implemented in sub-scale tests if the costs and risks of commercial-scale hardware implementation are inappropriate.

Status: *M-C Power is developing a "Mod-4" plate, which will incorporate several design improvements to the current plate design. M-C Power is internally reviewing the overall schedule and use of this design in mock-up tests and a future 250kW fuel cell.*

Subtask 3.5.2.1 Identify Advanced Plate Manufacturing Candidate Processes

Objective: Under the Product Development Test Program, M-C Power developed an advanced separator plate design, MOD 4. A prototype trial to define pressing, welding, cutting, and aluminizing parameters was also made.

Under this task, design modifications will be incorporated to address the deficiencies noted above. Finally, tests to quantify clamping force distribution and improvement made to the plate will be conducted. A second prototype run (50 plates) will be made in accordance with the revised design specifications. Once completed, the prototype run will be used to conduct an advanced full area stack test (AS-1).

Status: *M-C Power is developing a "Mod-4" plate, which will incorporate several design improvements to the current plate design. M-C Power is internally reviewing the overall schedule and use of this design in mock-up tests and a future 250kW stack.*

Subtask 3.5.3 Verify Advanced Component Cost Savings

Objective: Advanced component technologies developed and verified in bench-scale hardware under subtask 6.1 which have the potential to provide cost savings (either capital cost or operating cost) to the product will be transferred and scaled up to production in commercial-scale manufacturing equipment. Advanced component technologies will be evaluated in sub-scale stacks to verify performance, durability, manufacturability, and cost.

Status: *M-C Power is developing a "Mod-4" plate, which will incorporate several design improvements to the current plate design. M-C Power is internally reviewing the expected cost savings by using these type of components. Final costs are not available at this time.*

Subtask 3.5.3.1 Select Advanced Component Materials and Processes

Objective: Under this task, scale up of the stabilized Ni cathode and the LiNa electrolyte will continue. M-C Power has developed, under the PDT program, the know-how required for tape casting the stabilized Ni cathode and the LiNa electrolyte. Scale up to full area size components will be made under this subtask. Additionally, the sintering parameters of the stabilized Ni cathode will be characterized. Once the scale-up is completed enough, components to conduct a full area stack test (AS-1) will be manufactured.

Status: *M-C Power is continuing to experiment and test advanced components.*

Subtask 3.5.3.2 Define and Use 100cm² and 1000cm² Processes

Objective: The allocation provided under this subtask covers labor, materials and services needed to conduct bench scale test(s) in support of advanced development, manufacturing scale up or other technical issues needed by the program.

Status:

The near term advanced cell package has been defined as a stabilized cathode, a Li/Na electrolyte system, and a low Cr anode. This package was selected based on the recent cell tests at IGT which has exhibited stable performance for over 15,500 hours (test is ongoing) with one thermal cycle under atmospheric conditions and over 6,700 hours at 3 atm. with system conditions.

Li/Na Electrolyte

The analysis of a sample of vendor electrolyte powder was completed and was found to meet specifications. A final report of the results obtained from these analyses was issued. A purchase order for Li/Na powder was issued with an estimated arrival date of December, 1995.

Stabilized Cathodes

The stabilized cathode production powder was received from the vendor in August, 1995. Samples were collected and sent for scanning electron microscopy (SEM) and chemical analysis. The bulk density was measured and a benchtop cast was completed. The chemical analysis indicated that the composition used is acceptable. the SEM results show that the powder was insufficiently heat treated. X-Ray diffraction work will be completed next quarter to determine the acceptability of use for this mixture.

100 cm² size samples were sintered in a vendor furnace in a high hydrogen atmosphere. These parts exhibited larger shrinkages and were the strongest, most metallic parts manufactured to date.

M-C Power met with a vendor for the stabilized cathode powder to discuss modifications to the manufacturing process to improve the stabilizing agent distribution and increase the powder bulk density.

Ni-3 Cr Anodes

Scanning electron microscopy (SEM) analyses were received of a low Cr anode, the same type of anode being tested in 100cm² cell test M0195003. No residue Cr particles were apparent. The alloy composition was measured quantitatively using an EDX line scan of the cross section of five (5) particles. The results indicate that the manufacturing procedures developed for the PDT-1 Ni+6 Cr anode, including tape casting, sintering and the chromium milling procedures, are also acceptable for the Ni+3 Cr anode.

Water-Based Matrix Casting

Two (2) water based matrix tapes were cast. Water based casting would result in a cost savings largely due to the elimination of the need for solvent recovery. The water based tapes were strong and able to be removed from the substrate but had longitudinal microcracks indicating poor powder dispersion. The tapes cast with water based dispersants showed little apparent improvement in the tape cast properties. This work has been discontinued and a summary of the work to date completed.

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.

Subtask 3.6.1 Outline QA/QC Program Requirements

Objective: Quantitative goals such that progress can be objectively assessed will be developed.

Status: *No significant progress to report on this subtask during this reporting period.*

Subtask 3.6.3 Update QA/QC Procedures and Methods

Objective: Existing QA/QC procedures will be reviewed and revised to cover improvements made under previous DOE contracts. A primary focus of these procedures will be the planning and control of processes rather than inspection and remedial action. The revised procedures will then be integrated into M-C Power Quality Assurance Manual.

Status: *No significant progress to report on this subtask during this reporting period.*

Subtask 3.7 Analytical Testing

Objective: 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.

Subtask 3.7.1 Identify QA/QC Analytical Equipment Requirements

Objective: Future analytical needs will be assessed. The need for specific tests will be evaluated and the adequacy of analytical testing in providing useful data will be confirmed.

Status: *No significant progress to report on this subtask during this reporting period.*

Subtask 3.7.6 QA/QC Equipment Maintenance

Objective: The manufacturing facility will be maintained according to a regularly scheduled maintenance program has been developed and will be followed to ensure proper and reliable operation.

Status: *Regular maintenance is done on existing QA/QC equipment.*

TASK 4 PACKAGING AND ASSEMBLY

Objective: 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.

Status: *M-C Power does not anticipate completing or spending any money on task 4 activities in budget period 1. Therefore, these tasks are not shown in this report.*

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 5.1.1 Develop 50/250kW Pressurized Test Facility

Objective: Initial efforts to define and develop a pressurized 250 kW test facility to verify MCFC stack endurance in a plant configuration which could also simultaneously operate 50 kW pressurized stack tests are planned for the first budget period.

Status: *No significant progress to report on this subtask during this reporting period.*

Subtask 5.1.2 Maintain 20kW Atmospheric Test Facility

Objective: The existing DOE owned 20-kW atmospheric test facility is capable of testing commercial-area (1 m²) stacks. The facility will be maintained to ensure safe and reliable operation. Testing will be performed under subtask 6.4.

Status: *No significant progress to report on this subtask during this reporting period.*

Subtask 5.1.3 Maintain Acceptance Test Facility (ATF)

Objective: The ATF is a DOE-owned facility was built under DOE Contract No. DE-AC21-90MC27394 for conditioning and acceptance testing of 50-kW and 250-kW MCFC stacks. The ATF will be maintained to ensure safe and reliable operation.

Status: *General maintenance and improvements are being done to the ATF for future fuel cell stack conditioning needs. The majority of all maintenance and improvements have been implemented. All the repairs should be completed during the fourth quarter of 1995.*

Subtask 5.1.4 Develop Pressurized Bench-Scale Facility

Objective: Several 100 cm² test stands and one 1000 cm² stand will be designed, procured, and installed to support MCFC technology development. The test stands will be capable of simulating system operating conditions at elevated pressure. These stands will be used to generate performance data to assist in projecting the impact of improved cell technology on system performance.

Status: *Three (3) tests have been started this year under the PDI program. Updates on these tests are shown below.*

100 cm² Cell Test M0195001

This test was terminated after 1851 hours of pressurized operation due to wet seal failure caused by uneven and overly thick aluminization.

100 cm² Cell Test M0195002

This test was terminated after 1126 hours of operation, following a large decrease in the performance from 727 mV to 705 mV in one week.

100 cm² Cell Test M0195003

This cell test includes the first Li/Na electrolyte tested at M-C Power and a lower cost version of the stabilized cathode. Cell M0195003 has completed approximately 2975 hours of pressurized operation. The steady state performance at 60% fuel utilization, system gases and 3 atm. remains relatively steady at 760 mV at 16A with an OCV of 1029 mV.

Subtask 5.2.1 Review and Update 250-kW Facility

Objective: Under the PRDA program, M-C Power constructed and operated a 250 kW facility. The facility is located at the Unocal Fred L. Hartley Research Center, Brea, CA. The facility, after significant efforts, was commissioned and successfully operated very briefly. As a result of this effort, the start-up team (Bechtel, M-C Power, Stewart & Stevenson, and Unocal) believes that this facility represents the best chance of achieving timely testing of full-area, full-eight stacks - 250 kW class - in a cost effective way.

Status: *M-C Power has shut down the Unocal 250kW stack and is currently conducting a thorough evaluation of the stack at M-C Power's headquarters. Various alternatives are being investigated regarding the use of the Unocal facility as a test site.*

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.

Subtask 6.1.1 Active Component Unit Improvement

Subtask 6.1.1.1 Active Area Component Improvements

Objective: To complete development and verification of "Second generation" active components. IGT to document results and transfer data to M-C Power Corporation.

Status: *Inactive during this reporting period.*

Subtask 6.1.1.1.1 Improved Cathode Performance

Objective: Contractor (IGT) shall continue efforts to improve cathode performance and endurance, including creep resistance and microstructure. Contractor (IGT) shall document the effect of CaCO₃ addition to the cathode on cathode microstructure and wetting properties, primarily with Li/Na electrolytes. Contractor (IGT) shall document results with both physical mix and solid solution stabilized cathodes, clearly indicating any test conditions or post-test analyses which could confuse the conclusions.

Contractor (IGT) shall use the existing cathode microstructure and performance model to guide this effort.

Status: *This subtask is complete.*

Subtask 6.1.1.1.2

Objective:

Alternate Electrolyte

Contractor (IGT) shall review the need for pre-wetted (with Carbonate) matrix when fiber reinforcement is used using out-of-cell tests. Contractor (IGT) shall continue evaluation of alternate electrolytes, specifically the Li/Na/K/Ca system. Contractor (IGT) shall document ionic conductivity, liquids temperature, wetting properties, cathode dissolution, and cell corrosion as a function of melt composition through literature survey updates and cell testing results. Cell testing at the 100 cm² level will be conducted under Task 6.1.1.4.1 with post-test analysis conducted under this Task.

Contractor (IGT) shall continue operation of cell IGT-BSTC-66-93-4 and perform post-test analysis of cell IGT-66-94-1.

Status: *This subtask is complete.*

Subtask 6.1.1.1.3

Objective:

Strengthened Anode Fabrication

Contractor (IGT) shall provide a detailed written summary and oral presentation of the status of Ni-Al anode fabrication techniques, creep data, and cell test results. Contractor (IGT) shall critically compare competing techniques on a technical basis and relative to MAUS testing performed under a previous GRI program. Contractor (IGT) shall report on results using a Ni-CrOx anode.

Contractor (IGT) shall support M-C Power's evaluation of anodes made from pre-alloyed Ni-Al powders for compatibility with MCFC requirements. Such support will consist of participation in analysis of powder morphology and pre-test and post-test anode characterizations as well as definition of processing (sintering) conditions.

Status: *Topical report has been submitted. Therefore this subtask is complete.*

Subtask 6.1.1.1.4

Objective:

Cathode Dissolution

Contractor (IGT) shall quantify the effect on cell performance and cathode dissolution of stabilizer addition to the electrolyte through cell testing under Task 6.1.1.4.1. Contractor (IGT) shall identify cost-effective approaches to the stabilizer addition to the electrolyte and establish electrolyte taping procedures. Contractor (IGT) shall use Li/Na as the bulk electrolyte.

Status:

Subtask 6.1.1.1.5

Objective:

Alternate Cathode Material

Contractor (IGT) shall procure samples of alternate cathodes from Argonne National Laboratory and, if possible from ECN in the Netherlands. Contractor (IGT) shall perform the necessary characterizations to ensure proper matching of cathode, anode, and matrix. Contractor (IGT) shall perform parallel cell tests under Task 6.1.1.4 to compare Ni cathodes and stabilizing agent in the electrolyte, ANL's cathode, ECN's cathode, and stabilized Ni cathodes. Contractor (IGT) shall perform post-test analysis for these tests and report the results in a Topical Report.

In addition to the work being performed by IGT, Argonne National Laboratory will perform work related to cathode dissolution.

Status:

Note: Figures 1-10 referenced in this subtask are located at the back of this document.. The advanced cathodes currently being developed at Argonne National Laboratory are lithium Ferrite (LiFeO_2) and lithium cobaltate (LiCoO_2). Their transport to the anode is expected to be lower than that of NiO . The transport of LiFeO_2 is thought to be zero because Fe^{2+} is not reduced at the anode. Although Co^{2+} is reduced to metallic cobalt at the anode; the LiCoO_2 cathode has a lower rate of transport than NiO because of a significantly lower solubility in the MCFC Electrolyte (more than a factor of ten lower than NiO).

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 our prior work. The LiCoO_2 cathode, which has a resistivity of about $1 \Omega\text{-cm}$ without being doped, is being developed as a direct substitute for the lithiated NiO cathode.

Resistivities and Seebeck coefficients of the cathode materials are presented first. These were mainly measured in previous studies, but resistivity measurements were performed this quarter on a new doubly doped LiFeO_2 composition. Recent studies of the $\text{LiFeO}_2\text{-LiCoO}_2\text{-NiO}$ phase diagram are presented next. These studies are being conducted to aid in optimizing the composition of the doubly doped LiFeO_2 cathode. Finally, our recent MCFC tests of LiCoO_2 and LiNiO_2 ,

The data in Table 1 shows that the resistivity of the LiFeO_2 cathode material is decreased significantly by substituting Ni, Co, or both Ni and Co for a portion of the Fe.

Resistivities as a function of mole fraction CO_2 in $\text{O}_2\text{-CO}_2$ mixtures are shown in Fig. 1 for four of the cathode materials. The values near 0% of CO_2 in Fig. 1 differ slightly from the values listed in Table 1. This is due to minor differences in composition between batches. The resistivity of the doubly doped materials, $\text{Li}_7\text{Fe}_6\text{NiCoO}_{16}$, was similar to that of LiCoO_2 at low mole fractions of CO_2 , but increased with increasing CO_2 mole fraction. This resistivity increase is believed to be due to reduction of Ni^{3+} to Ni^{2+} along with precipitation of Li_2CO_3 at higher CO_2 concentrations. The Li_2CO_3 product was identified by X-ray diffraction on the sample after equilibration at a high partial pressure of CO_2 . Our recent MCFC tests have employed the composition $\text{Li}_7\text{Fe}_6\text{CoNiO}_{15}$, because it is more stable in the cell environment (it has a constant resistivity of about $5 \Omega\text{-cm}$ at 650°C in $\text{O}_2\text{-CO}_2$ mixtures).

The resistivity of Co-doped LiFeO_2 , plotted in Fig. 1 on a logarithmic scale, is plotted in Fig. 2 on a linear scale. A local minimum is seen at an $\text{O}_2\text{-to-CO}_2$ ratio of 4:1. The Co-doped LiFeO_2 cathode performs well only at this $\text{O}_2\text{-to-CO}_2$ ratio. This behavior of the Co-doped LiFeO_2 is discussed further in the last section of this report.

Seebeck coefficients were measured for many of the materials listed in Table 1, and are shown in Fig. 3. These materials are p-type conductors; all of the better cathode materials have this in common. The anode material, nickel, is an n-type conductor.

PHASE DIAGRAM STUDIES

The solubilities of NiO and LiCoO₂ in LiFeO₂ are being measured to aid in optimizing the doubly doped LiFeO₂ cathode composition. Compositions along the NiO-LiFeO₂ join were prepared and were then characterized by X-ray diffraction, scanning electron microscopy, and resistivity measurements. The smooth variation in cubic lattice parameter with NiO concentration indicates that there is complete solid solution from one end of the join to the other (see Fig. 4). No other phases were detected by X-ray diffraction or microscopy. The resistivity of the solid solution, measured at 650°C in air, decreased with increasing NiO concentration. At 50 at% NiO, the resistivity was 4.5 Ω-cm; at 87.5 at% NiO, it was 0.4 Ω-cm. X-ray diffraction results for the LiCoO₂-LiFeO₂ and NiO-LiCoO₂ joins will be reported next quarter.

MCFC TESTS

The effects of porosity in 25-cm² LiCoO₂ cathodes are being investigated. The porosity is altered by changing the fibers-to-fines ratio in the cathode. (The fibers are made by spraying a suspension of powder in organic binders and subsequently firing them). The ratios investigated during this quarter were 2:1 and 3:1 fibers-to-fines. Typical polarization curves are given in Fig. 5. The 3:1 ratio appears to be slightly better than the 2:1 ratio. A cathode consisting of a 4:1 ratio of fibers to fines is currently on test. The results will be reported next quarter.

As part of our work to understand and improve the doubly-doped LiFeO₂ cathode, singly doped cathodes were tested in MCFCs. The cathodes were doped with either 12.5 mol% Ni or 12.5 mol% Co on the Fe sites in the lattice. The MCFCs were operated with O₂-CO₂ gas mixtures to simulate pressurized operation at 3-5 atm. At various times during the operation, measurements of the effect of O₂-to-CO₂ ratio on the MCFC voltage at 160 mA/cm² were conducted.

Each voltage, V, was converted to an area specific resistance (ASR) using the equation:

$$ASR = (V^o - V) / I \cdot p \quad [1]$$

were V^o is the open-circuit voltage, I is the current density (0.150 A/cm²), and p is the product of the fast resistance, as measured by a current-interrupt technique, and the MCFC area. Measurements of this type from prior experiments are shown in Fig. 6. The minimum seen in the curve for Co-doped LiFeO₂ is not understood. However, it appears to correspond to a similar minimum in the resistivity for this material (see Fig. 2). This behavior was further studied in the test of the Ni-doped and Co-doped LiFeO₂ cathodes described below. The other three curves in Fig. 6 show the type of behavior desired (a low ASR over a broad range of O₂-to-CO₂ ratios). These are the best we have obtained to date for NiO, LiCoO₂, and doubly doped LiFeO₂.

The potential at 160 mA/cm² versus time for the MCFC with the Ni-doped LiFeO₂ cathode is given in Fig. 7. In Fig. 8, the effect of CO₂ mole fraction in the cathode gas on the area specific resistance of the MCFC is plotted for three different times during the test. The ASR curve exhibits a minimum early in the test. The curve tends to flatten out and broaden with time.

The potential at 160 mA/cm² versus time for the MCFC with the Co-doped LiFeO₂ cathode is given in Fig. 9. In Fig. 10, the effect of CO₂ mole fraction in the cathode gas on the area specific resistance of the MCFC is plotted for four different times during the test. The ASR curve again exhibits a minimum early in the test, and the curve tends to flatten out and broaden with time. Thus, the minimum is a transitory phenomenon that does not impact on the long-term performance of the cathode.

Both cells have been examined for migration of dopants from the cathode into the electrolyte tile. The migration was very low. In particular, the high migration of cobalt from the doubly doped LiFeO₂ (see last report) was not explained by the results of these experiments with single dopants.

Subtask 6.1.1.2

Objective:

Alternate Cell Package Development

To simplify cell and stack fabrication, assembly, and conditioning through modified cell package and component design, integrated manufacturing, and out-of-cell conditioning.

Subtask 6.1.1.2.1

Objective:

Alternative Cell Package Design & Development

Contractor (IGT) shall continue development and evaluation of cell package designs which involve elimination of electrode ledges to reduce differences in stiffness between the wet seal and active areas of the cell. Contractor (IGT) shall quantify the effect of direct contact of electrodes with the opposing gas (i.e., anode and oxidant, cathode and fuel). Contractor (IGT) shall evaluate cell sealing approaches including a matrix "gasket", electrode densification (coining), and "welding" of electrode and/or current collector to the plate. Contractor (IGT) shall conduct verification testing in 100 cm² under Task 6.1.1.4.2 with appropriate atmospheres and pressure differentials. Contractor (IGT) shall design and construct out-of-cell screening tests for edge sealing evaluation.

Status:

Alternative Cell Package Design and Development

A special 6" x 6" 2-cell stack was designed and fabricated to test electrodes to the edge. The purpose of this subtask is to determine the effects of the gas atmosphere on electrodes exposed to opposing gases; that is, the effect of the oxidant air on the anode and of the fuel on the cathode. A total of two cell tests were conducted this quarter to determine the effects of opposing gas atmospheres on electrodes extended to the edge.

Cell IGT-BS-TC-42-95-3

The purpose of this two cell (6" x 6") stack test conducted with aluminum foil for electrode edge protection is to determine any deleterious effects of the gas atmospheres on the electrodes exposed to opposing gases in the manifolds and peripheral edges during cell operation.

Overall Cell IGT-BS-TC-42-95-3 with both electrodes extended to the edge performed significantly better than the first cell test IGT-BS-TC-42-95-2. The initial OCV's for the stack, Cell 1 (bottom), and Cell 2 (top) were within 81 mV, 47 mV, and 35 mV of the theoretical values of 2086 mV and 1043 mV, respectively. Therefore, the OCV and performance of the 2-cell stack gradually decreased with time. The drop in OCV and performance values is primarily due to the existence of the parasitic currents between the cell active area, gas manifolds, and the cell peripheral edges. GC gas analyses conducted on the fuel outlet at OCV confirmed the existence of these parasitic currents which increased in magnitude from 45 mA/cm² to 82 mA/cm² with time. In view of OCV and performance decay with time, Cell IGT-BS-TC-42-95-3 was voluntarily terminated after 187 hours of operation.

Based on the post-test disassembly observations of Cell IGT-BS-TC-42-95-3 it was clear that the protection of the anode around the outside edge and around oxidant manifolds is crucial. Oxidation of the anode causes parasitic cells to develop which will reduce the OCV. Therefore, a third 2-cell stack was assembled and started during September. This third test, Cell IGT-BS-TC-42-95-4 is basically a repeat of the second test IGT-BS-TC-42-95-3 with the following exceptions.

- 1. Electrodes were protected by wrapping with a thicker aluminum.*
- 2. For the anode and cathode both the peripheral and the edges exposed to all the four manifolds (two fuel and two oxidant) were protected with the aluminum foil.*

The initial OCVs for the stack, Cell 1 and Cell 2 for Cell IGT-BS-TC-42-95-4 were within 165 mV, 89 mV, and 76 mV of the theoretical values of 2086 mV and 1043 mV, respectively. Also, GC analyses conducted on the fuel outlet at OCV indicated the existence of a parasitic current of 41 mA/cm². The anode and cathode wet seal efficiencies are 97% each and the nitrogen crossover is 3.6%. This shows that even the 2 mil thick aluminum foil did not effectively protect the edges of the electrodes and alternatives have to be found. The steady state performance data of this cell test will be reported next month.

Subtask 6.1.1.2.2

Objective:

Advanced Cell Package Fabrication

Contractor (IGT) shall, under the IHI program, define and evaluate approaches and techniques for laminating active cell components during initial manufacture. Contractor (IGT) shall address cutting and handling of "green" laminates.

Contractor (IGT) shall process "green" laminates into cell packages and conduct verification testing in 100 cm² single cells under this Task.

Status:

See subtask 6.1.1.1 write up.

Subtask 6.1.1.2.3

Objective:

Out of Cell Component Preconditioning

Contractor (IGT) shall, under the IHI program, define and evaluate techniques for out-of-cell conditioning of the laminated cell packages prepared under Task 6.1.1.2.2. Contractor (IGT) shall demonstrate the performance in 100 cm² under this Task. Contractor (IGT) shall address cutting of conditioned laminates using

techniques amenable to mass production at commercial scale.

Status:

A series of lamination tests were performed in an effort to obtain flatter and more compact laminates. To improve flatness and reduce cathode expansion during ex-situ oxidation, laminates were pre-conditioned according to the normal procedure, but just before cool down, a pressure of 0.5 psi was momentarily applied through a rod that rested on the perforated plate that covered the laminate. The results were reproducible. Although the laminates were flatter, the extra force caused the matrix to become embossed by the perforated plate cover and it had little effect on the expansion of the cathode upon oxidation. The use of extra force is therefore not recommended.

However, out-of-cell preconditioning was simplified by reducing the number of perforated plates need from two to one. When the laminate is pre-conditioned out of cell, the cathode side is at the bottom and supported on a perforated stainless steel plate which is in turn supported by an alumina plate. The idea of the perforated plate is to allow air to permeate into the inner area of the cathode for complete cathode oxidation. In addition to the bottom perforated plate, another perforated plate is on top of the laminate so that a load can be applied to the laminate to maintain flatness during the process. Test were conducted to determine if, by placing the laminate matrix side down directly against the alumina support plate, the bottom perforated plate can be eliminated. The matrix side of the laminate was placed directly on an alumina plate heavily sprayed with a graphite coating. A perforated plate was placed on top of the laminate and ceramic pellets who total weight provides a 0.2 psi load in the laminate was spread over the top perforated plate. The assembly was heated at a rate of 40°C and then held at 650°C for 2 hours. It was allowed to cool down in the furnace.

Efforts are being made to increase the active cathode surface area. One method is to use high surface area Ni. To provide large pores for efficient gas transport, the high surface area powder will be formulated in such a way that it forms a foamed structure. Initial attempts at making the foamed structure have been encouraging. Pore size distribution of the preliminary porous structure shows pores for efficient gas transport. The process is now being scaled up to prepare 100-cm² size cathode for cell testing.

Cell IGT-BS-TC-42-95-1

Cell IGT-BS-TC-42-95-1 was assembled with the first version laminate and the cathode current collector both extended to the wet seal. The only other active component provided was a Ni+5Cr anode which was placed within the housing along with a perforated nickel current collector. The purpose of this test was to evaluate the performance of the out-of-cell preconditioned laminated package fabricated with the Li/Na electrolyte. Startup of this cell occurred on May 1, 1995. The reference fuel and oxidant gas flows were set for 75% fuel and 50% oxidant utilizations at 160 mA/cm².

Cell IGT-BS-TC-42-95-1 operated for 2161 hours and was terminated to preserve the post-test analysis integrity. This cell was successfully thermal cycled twice during its operation and the performance at 160 mA/cm² was stable at 788 mV after each thermal cycle. The anode and cathode wet seal efficiencies were 97%

and 100%, respectively, and the nitrogen crossover was low at 0.7%.

The post-test analysis of Cell IGT-BS-TC-42-95-1 was completed this quarter and is presented below.

Post Test Analysis of Cell IGT-BS-TC-42-95-1

Post mortem analyses showed intimately bonded components. However, the cathode was highly embossed with the perforated cathode current collector because of a high initial porosity.

The post-test carbonate inventory showed a small amount of carbonate loss, 0.99g. The electrolyte filling of components was 95% for the matrix, 30% for the anode and 41% for the cathode. Because of low electrolyte loss, the post test electrolyte composition is still close to the starting carbonate composition. In other words, the liquidus temperature of the electrolyte remains well above 500°C according to the phase diagram..

Subtask 6.1.1.3

Objective:

Corrosion, Modeling and Performance

To test separator plate materials in bench-scale fuel cells. To maintain and upgrade the Cathode Performance Model. To increase and optimize the active cell package performance.

Subtask 6.1.1.3.1

Objective:

Corrosion

Contractor (IGT) shall analyze post-test separator plate materials from 100 cm² cells operated under Task 6.1.1.4. The separator plate materials will be specified by Professor Robert A. Rapp of Ohio State University under a parallel subcontract with M-C Power. Contractor (IGT) shall supply post-test metallographic analysis and cell operating data to Professor Rapp and participate in a review meeting at M-C Power.

Status:

No significant progress to report on this subtask during this reporting period.

Subtask 6.1.1.3.3

Objective:

Performance

Contractor (IGT) shall continue efforts to improve MCFC performance including stability.

Subtask 6.1.1.3.3.1

Objective:

Define Baseline Cell Package

Contractor (IGT) shall define the Baseline Cell Package and propose improvements within 30 days of contract execution. The definition shall include raw materials, processing procedures, component dimensions, startup procedures, and typical performance and stability.

Status:

This subtask was completed..

Subtask 6.1.1.3.3.2

Objective:

Define Initial Advanced Cell Package

Contractor (IGT) shall define an initial Advanced Cell Package using Li/Na electrolyte, NiAl anode, and cathode stabilization (either by CaCO₃ in the electrolyte or the cathode) based on data obtained in prior programs. Contractor (IGT) shall perform cell tests of the advanced cell package under subtask 6.1.1.4 and use the results to modify and improve the Advanced Cell Package. Post-test

analysis will be conducted under this subtask.

Status: *This subtask was completed.*

Subtask 6.1.1.3.3.3 Define Performance Limits

Objective: Contractor (IGT) shall estimate the limits of performance (current density, voltage) at present systems conditions and propose ways to achieve the limit, emphasizing cell components. Contractor (IGT) shall propose approaches to double the current density.

Status: *Efforts are being made to increase the active cathode surface area. One method is to use high surface area Ni. To provide large pores for efficient gas transport, the high surface area powder will be formulated in such a way that it forms a foamed structure. Initial attempts at making the foamed structure have been encouraging. Pore size distribution of the preliminary porous structure shows pores for efficient gas transport. The process is now being scaled up to prepare 100 cm² size cathode cell testing.*

Subtask 6.1.1.3.3.4 Optimize Cell

Objective: Contractor (IGT) shall fabricate components based on the finding of Task 6.1.1.3.3.3 for testing in 100 cm² cells under subtask 6.1.1.4.

Status: *Decrease Cathode Tortuosity*

Approach: We used computer modeling 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 the cathode performance would be to increase the surface used for the electrochemical reaction and to decrease cathode tortuosity. For this purpose we are attempting to align the pores perpendicular to the plane of the electrode. This will decrease tortuosity, shortening the path length for the ionic and electrical currents transport in the cathode by orienting the pores perpendicular to the plane of the electrode, resulting in improved cathode performance.

One of these tapes was used green in a 3-cm² Cell (1-MOLS, discussed below). Another tape was sintered for 30 minutes at 950°C under a 10%H₂/90%N₂ atmosphere. A good structure was obtained and another cell was assembled, Cell 2-MOLS.

During September we stopped Cell 1-MOLS, which had been started in August with a green tape, and started Cell 2-MOLS with a sintered tape.

Cell 1-MOLS. (Terminated after 984 hours)

This 3-cm² cell was started with a green Ni cathode with aligned pores. The cell performance is presented in Figure 6.1.1.3.3.4.1. As seen in the figure, the cell potential was 896mV at 160 mA/cm² after 24 hours of operation, 915mV after 72 hours and remained at more than 920 mV through 850 hours. This is the longest a performance so high has been seen in 3 cm² cell. Other cells have achieved high performance but have rapidly decayed. The high cell performance is due to lower cell IR-drop (45 mV equivalent to 2.8 mΩ in a 100 cm² cell) resulting from very low resistance of the cathode. The cathode polarization is 58 mV, which is

better than average for an MSP Ni electrode. Table 6.1.3.3.4.1. compares the performance of 1-MOLS with the performance of a standard state-of-the-art cell.

Cell 2-MOLS.

This cell began life exhibiting poor performance. It used a cathode with aligned pores that was sintered before cell assembly. The cathode tape had many void-like cavities caused by trapped bubbles of air during taping. Currently the cell shows 930 mV cell potential at 160 mA/cm², with 44 mV cathode polarization, 32 mV anode polarization, and 53 mV IR-drop. The cathode polarization (44mV) and the cathode IR (40 mV) are somewhat high, compared to that obtained in Cell 1-MOLS, probably due to the voids caused by the trapped air during the taping.

Table 6.1.1.3.3.4.1. PERFORMANCE OF CELL 1-MOLS WITH A STANDARD CATHODE

<i>Current Density mA/cm²</i>	<i>Cell Potential MOLS/Std</i>	<i>Polarization*</i>		<i>IR-Drop*</i>	
		<i>MOLS/Std Cathode</i>	<i>MOLS/Std Anode</i>	<i>MOLS/Std Cathode</i>	<i>MOLS/Std Anode</i>
<div>-----mV-----</div>					
<i>80</i>	<i>996/978</i>	<i>27/31</i>	<i>13/14</i>	<i>12/21</i>	<i>11/12</i>
<i>160</i>	<i>930/897</i>	<i>58/65</i>	<i>25/30</i>	<i>24/42</i>	<i>22/25</i>
<i>240</i>	<i>861/813</i>	<i>92/99</i>	<i>36/44</i>	<i>36/53</i>	<i>37/33</i>

* Total polarization and IR-drop is obtained
 by adding the cathode and anode polarization and IR-drop

Thin Anode

The approach being developed have is to substantially reduce the thickness of the anode and anode current collector without sacrificing performance. The anode is prepared by applying slurry onto a green lithium aluminate tape thus avoiding the cost of sintering anode.

Powder Preparation:

During August we prepared two more slurries. Cells 3-PALS were assembled with these slurries. Cells 5-PALS was assembled using a slurry of Ni-3Al alloy powder for the anode.

Cell 3-PALS:

Cell 3-PALS had a Ni-2wt%CR₂O₃ anode with a Ni expanded metal anode current collector over a 3-rib separator plate section, a Ni cathode and standard cathode current collector and matrix. This test reached 894 mV cell potential at 160 mA/cm² after 48 hours of operation but decayed to a steady state potential of 860 to 865 mV. At the peak 894 mV potential the cell showed 42 mV anode polarization, 50 mV cathode polarization and 47 mV IR-drop; this performance is within normal limits. The cell performance of Cell 3-PALS is compared with that of a standard cell in Figure 6.1.1.3.3.4.3. The anode polarization of Cell 3-PALS (42 mV) is very slightly higher than that of a standard cell, where 30 to 34

mV are obtained at 160 mA/cm² but it shows that low anode polarization and normal IR-drop are achievable with the novel anode. The life graph of Cell 3-PALS, operated 528 hours, is presented in Figure 6.1.1.3.3.4.4; as seen in the figure, the decay from 894 mV cell potential at the peak to 860 mV at steady state was caused by an increase in the anode polarization from 42 mV to 88 mV. The cathode polarization decreased from 50 to 35 mV. The decay in the anode polarization indicates that anode surface area is decreasing due to sintering and that further improvement in the powder preparation is needed. Visual examination of the components on termination, showed that the anode was in good contact with the electrolyte matrix. The expanded metal showed a slight separation from anode at the rib channels.

Cell 4-PALS:

Cell 4-PALS was started with a Ni₂wt% LiAlO₂ anode and a Ni expanded metal anode current collector over a 3-rib separator plate section, a Ni cathode and a standard cathode current collector and matrix. Cell 4-PALS reached only 785 mV cell potential at 160 mA/cm² due to high anode polarization and high anode resistance and was quickly terminated after only 100 hours of operation. The anode polarization and the IR-drop at 160 mA/cm² were 105 mV and 103 mV, respectively, compared to 30 to 35 mV and approximately 65 mV, respectively, for the a standard cell. On termination, a visual examination of the components revealed that the anode had developed cracks and had some holes (poor integrity) and was making poor contact with the expanded metal.

Cell 5-PALS:

This 3-cm² cell was started in September with a Ni-3Al anode, a Ni expanded metal anode current collector backed by a 3-rib separator section, a Gould Ni cathode, reinforced matrix and standard Li/K electrolyte. The cell reached 883 mV at 160 mA/cm² after 72 hours of operation, with 38 mV anode polarization and 61 mV IR-drop. This performance is below average. The life graph of Cell 5-PALS is shown in Figure 6.1.1.3.3.4.5.

Subtask 6.1.1.4 Objective:

Verification Testing

To provide cell testing support for subtasks 6.1.1.1, 6.1.1.2, and 6.1.1.3 and for M-C Power.

Contractor (IGT) shall conduct 100 cm² single-cell tests in support of the other tasks in this program. Contractor (IGT) shall install and commission four pressurized 100 cm² single cell test facilities.

Status:

Bench-Scale Testing

Cell IGT-PDI-1

The purpose of this cell test is to evaluate the baseline characteristics of the Li/Na electrolyte at 1 and 3 atm pressures with system gases. The cell performance as a function of time and pressure is shown in Figure 6.1.1.4.1.1. The data indicate that the cell performance at 1 atm and 160 mA/cm² (75% of U₀) increased from 660 mV to 708 mV due to a decrease in Ir (32mV) and polarization (16mV). The average OCV of the cell is 1000 mV, which is 10 mV higher than the theoretical value of 990 mV at 1 atmosphere pressure. The cell was then pressurized to 3 atm

under system conditions. The cell performance at these conditions and a current density of 160 mA/cm², increased from 732 mV to 745 mV due to a decrease in polarization. The observed performance improvement of 37 mV from 1 to 3 atm is ~ 33% lower than that predicated by the PSI model. The OCV varied from 1013 mV to 1027 mV with an average of 1020 mV, ~ 12 mV higher than the theoretical value of 1008 mV. The anode wet seal efficiency was initially high at 100% at 1 atm but decreased to 81% at 3 atm. The cause for the low anode wet seal efficiency is being investigated. The cathode wet seal efficiency is 100%. Also the nitrogen crossover was initially high at 3.6% (1 atm) and decreased to 1.7% when the cell was pressurized to 3 atm. To date, the cell has operated for ~ 650 hours and will continue its operation for an additional 1350 hours to reach its goal of 2000 hours of operation under system conditions.

Cell IGT-PDI-2

The purpose of this cell test is to establish the baseline characteristics of a cell having a cathode stabilizing agent added to the electrolyte at 1 and 3 atm pressures under system conditions. The cell performance as a function of time and pressure is shown in Figure 6.1.1.4.1.2. The data indicate that the cell performance at 1 atm and 160 mA/cm² increased from 633 mV to 684 mV due to a decrease in IR (39 mV) and polarization (12mV). The average cell OCV is 994 mV, 4 mV high than the theoretical value of 990 mV. The cell was then pressurized to 3 atm under system conditions at about 432 hours of operation. The cell performance under these conditions and 160 mA/cm² is about 755 mV. The observed performance improvement of 71 mV from 1 to 3 atm is ~ 29% higher than that predicted by the PSI model. The average OCV was 1016 mV, 8 mV higher than the theoretical value of 1008 mV. The anode and cathode wet seal efficiencies are 100% each. The nitrogen crossover was initially high at 3.9% but later decreased to 1.0% when the cell was pressurized to 3 atm. To date, the cell has operated for 624 hours and will continue its operation next month.

Cell IGT-PDI-2

The purpose of this cell test is to establish the baseline characteristics of a cell having added to the electrolyte at 1 and 3 atm pressures under system conditions. The cell performance as a function of time and pressure is shown in Figure 6.1.1.4.1.2. The data indicate that the cell performance at 1 atm and 160 mA/cm² increased from 633 mV to 684 mV due to a decrease in IR (39 mV) and polarization (12 mV). The average cell OCV is 994 mV, 4 mV higher than the theoretical value of 990 mV. The cell was then pressurized to 3 atm under system conditions at about 432 hours of operation. The cell performance under these conditions and 160 mA/cm² is about 755 mV. The observed performance improvement of 71 mV from 1 to 3 atm is ~ 29% higher than the theoretical value of 1008 mV. The anode and cathode wet seal efficiencies are 100% each. The nitrogen crossover was initially high at 3.9% but later decreased to 1.0% when the cell was pressurized to 3 atm. To date, the cell has operated for 624 hours and will continue its operation next month.

100cm² Cell Test IM9501

The purpose of this test is to determine the baseline operating characteristics of a lower cost matrix. This test was terminated after 262 hours of operation. The cell had an extremely high IR and would not hold a current of more than 2 A out

of 16 A. The resistance decreased in the last week prior to termination.

100cm² Cell Test IM9502

The purpose of this test is to determine the baseline operating characteristics of a Ni-Al anode with the Li/Na electrolyte. A stabilized cathode was manufactured to match with the Ni-Al anode obtained from the manufacturing trials. This test completed 936 hours of operation at 3 atm. and system conditions as of October 2, 1995. Performance has decreased from 748 mV to 729 mV during the last week of the quarter.

100cm² Cell Test IM9503

This test completed 934 hours of steady operation at 3 atm and system conditions as of October 2, 1995 and continues operation. Performance remains steady at 762 mV.

100cm² Cell Test IM9504

This test will be a repeat of IGT cell test BSTC-66-94-1, which was terminated after 6700 hours of pressurized operation. The components have been manufactured and this cell will be assembled during the next quarter.

100cm² Cell Test IM9505

This was a test of a cell package cut from cell #250 of the Unocal stack. This test was terminated after 150 hours of operation due to high IR and the inability to load the cell above 40 mA/cm². The observed performance was similar to that obtained in the Unocal 250kW stack.

100cm² Cell Test IM9506

Parts were manufactured this quarter and the pre-test analysis and test plan were completed. This test will be a pressurized 100 cm² cell test of a thinner cell package of the stabilized cathodes and Li/Na electrolyte. This test will begin heating up next month.

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.

**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 Operation	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.	In Operation	14882	Longest operating Li/Na cell ever recorded. (Operating at the continuous load of 160 mA/cm ²)
IGT-BS-TC-66-94-1	Determine performance characteristics of the Li/Na electrolyte under pressurized operation (3 atm) using system gases.	Terminated	6908	No evidence of Ni-shortening. Matrix thinned down by 25% and the electrolyte loss was 2.0 g. The large matrix compaction is believed to be the cause of wet seal leakage experienced t
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 to be flattened by pressure during preconditioning.
IGT-BS-TC-42-95-2	To test electrodes to edge and determine the effects of opposing gas atmospheres 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 atmospheres 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.
STET	To determine the performance of a cell package taken from the active area of the UNOCAL 250 cell stack. The whole cell package including the current collectors was extended to the outer edge of the wet seals.	Terminated	187	Cell did not perform well due to high IR.

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-BS-TC-66-93-4	1488	1024	737	64	223	89	99	4.0
IGT-PDI-1	648	1013+	745+	34+	234+	81	100	1.7
IGT-PDI-2	624	1015+	753+	38+	224+	100	100	1.0
MCP IM9502	648	1026+	690+	50+	286+	84	100	1.1
MCP IM9503	654	1018+	727+	50+	241+	99	100	0.8

* At a current density of 160 mA/cm².

+ Under system conditions, 75%U_F and 40% U_O.

Subtask 6.2.1 Buss Bar Material Selection

Objective: Designs will be developed and materials selected to connect the stacks in series, to minimize resistance and to minimize the complexity of vessel penetration.

Status: *Preliminary investigation work is ongoing to support this activity.*

Subtask 6.3 Balance of Plant Component Development

Objective: In this task, Bechtel's first 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

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.

Subtask 6.4.1 Fabricate and Operate 20kW Non Pressurized Stacks

Objective: Two commercial-area short stacks (20-kW) will be fabricated and operated at atmospheric pressure to verify new separator plate concepts, advanced component technologies, manufacturing scale-up, modified stack start-up and operating procedures, and commercial stack fixturing.

Subtask 6.4.1.1 Stack AS-1 (20kW) Fabricate and Operate

Objective: Stack AS-1 will be used to qualify the baseline cell package. Preliminary work effort will be performed during the first budget period; however, fabrication and testing will occur in a later budget period.

Status: *No significant progress to report on this subtask during this reporting period.*

Subtask 6.4.4 Stack Failure Mode Verification

Objective: M-C Power, under the Product Development Test Program, completed a highly successful full-area, short-height stack test - MCP-7. Under this subtask, an allocation is provided to continue stack operations. The purpose of the continuing stack operations is to validate, if necessary, the Unocal failure mode. M-C Power believes that confirming the failure mode in a full-area stack is necessary to develop customer confidence.

Status: *M-C Power did continue the stack test to collect additional data. The test has since been shut down.*

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: *No significant progress to report on this subtask during this reporting period.*

Subtask 6.5.3.2.2 **Manufacture 1 MW Electrolyte Matrix Tapes**

Objective: Repeat components will be fabricated for the power plant. Some initial production techniques will be tested prior to full production.

Status: *No significant progress to report on this subtask during this reporting period.*

Description of Attachments

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

Thomas G. Benjamin
T. G. Benjamin, PDI Project Manager - Date

DOE Reviewing Representative

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

Date: January 8, 1996

Contractor: M-C Power Corporation

Contract No.: DE-FC21-95MC30133

The following deliverables are submitted in compliance with the contract reporting requirements checklist:

Report/Plan	Form No.	Reporting Period	No. of Copies
A. GENERAL MANAGEMENT:			
___ Management Plan	None		
___ Status Report	None		
___ Summary Report	1332.2		
B. SCHEDULE/LABOR/COSTS:			
___ Milestone Schedule/Plan	1332.3		
___ Labor Plan	1332.4		
___ Cost Plan	1332.7		
___ Milestone Schedule/Status	1332.3		
___ Labor Management Report	1332.8		
___ Cost Management Report	1332.9		
C. EXCEPTION REPORTS:			
___ Conference Record	None		
___ Hot Line Report	None		
D. TECHNICAL:			
<u>X</u> Technical Progress Report	None	4/1/95 to 6/30/95	3
<u>X</u> Draft for Review	None	4/1/95 to 6/30/95	3
___ Final for Approval	None		
___ Topical Report	None		
___ Draft for Review	None		
___ Final for Approval	None		
___ Final Technical Report	None		
___ Draft for Review	None		
___ Final for Approval	None		
___ Software	None		
___ Other (Specify) _____			
E. OTHER:			
___ Property Inventories	See DEAR 945		
___ Subcontracting	SF 294		
___ Request For Patent Clearance for Release of Contracted Research Documents	METC Form	N/A	

Fig. 1. Resistivities of Cathode Materials at 650°C
in O_2 - CO_2 Mixtures

Fig. 2. Resistivity of Co-Doped LiFeO_2
at 650°C in O_2 - CO_2 Mixtures

Fig. 3. Positive Seebeck Coefficients are Indicative of the p-Type Conductivity Required in MCFC Cathodes.

Fig. 4. Cubic Lattice Parameter for NiO-LiFeO_2 Solid Solutions.

Fig. 5. Polarization Curves for Two Ratios of Fibers to Fines, 3:1 and 2:1

Fig. 6. Area Specific Resistances at 160 mA/cm² in MCFCs Employing Co-Doped LiFeO₂, Doubly Doped LiFeO₂, LiCoO₂, or NiO Cathodes

Fig. 7. Potential at 160 mA/cm² vs. Time for an MCFC with a Ni-doped LiFeO₃ Cathode.

Fig. 8. Area Specific Resistance (ASR) for an MCFC with a Ni-doped LiFeO_2 Cathode.

Fig. 9. Potential at 160 mA/cm² vs. Time for an MCFC with a Co-doped LiFeO₂ Cathode.

Fig. 10. Area Specific Resistance (ASR) for an MCFC with a Co-doped LiFeO_2 Cathode.

Figure 6.1.1.3.3.4.1. LIFE GRAPH OF CELL 1-MOLS

Figure 6.1.1.3.3.4.2. LIFE GRAPH OF CELL 2-MOLS

Figure 6.1.1.3.3.4.3. POLARIZATION OF CELL 3 PALS

Figure 6.1.1.3.3.4.4. LIFE GRAPH OF CELL 3-PALS

Figure 6.1.1.3.3.4.5. LIFE GRAPH OF CELL 5-PALS

Figure 6.1.1.4.1.1. LIFE PLOT OF IGT-PDI-1

Figure 6.1.1.4.1.2. LIFE PLOT OF IGT-PDI-2