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EXECUTIVE SUMMARY

This sixteenth quarterly technical progress report of the MHD Integrated Topping Cycle Project presents the accomplishments during the period May 1, 1991 to July 31, 1991. A summary of the work completed during this reporting period is presented in this Executive Summary.

SYSTEMS ENGINEERING (SECTION 3)

The Interface Document is in the process of being updated. A complete instrumentation list is being added.

The High Voltage Room requirements for the prototypical power train were reviewed in conjunction with the Channel Requirements Document.

The overall integrated schedule for MSE, TRW, Avco/TDS, and Westinghouse was reviewed.

Program personnel attended the 29th Symposium on Engineering Aspects of Magnetohydrodynamics (SEAM).

COMBUSTION SUBSYSTEM DESIGN AND FABRICATION (SECTION 4)

Manufacturing of the slagging stage exit section flat cooling panels, the coal injector hot sleeve, and the precombustor combustion can has been completed. Manufacturing of other exit section cooling panels, the end plate cooling panels and pressure shells is in progress.

Welding fixtures and schedules for the slagging stage baffle and precombustor transition ring were finalized.

A cooling panel backside corrosion protection procedure has been developed.

A Conceptual Design Review for the Low Pressure Cooling System (LPCS) was held and the procurement of several long lead items was approved.

The design of assembly and shipping fixtures was completed and their manufacturing is close to completion.

PROTOTYPICAL CHANNEL DESIGN (SECTION 5)

Work has been initiated on the fabrication of channel related prototypical hardware. The cathode wall fabrication is complete, the sidewall element fabrication is underway and anode procurements have begun. The channel and diffuser are scheduled to be delivered to the CDIF in May 1992.

The sidewall behavior in the Mark VII channel was analyzed in order to provide confirmation for the prototypical sidewall design. The electrical characteristics of straight-bar wall and Z-bar wall sidewalls were compared in unslagged Mark VII generator tests. This data supplemented slagging generator test data obtained earlier, and was used to study the effects of bar segmentation on interbar voltages and interbar fault power. Results indicated that interbar voltages, and hence fault power, are lower with Z-shaped sidebars.

Sidewall wear data from 1A4 design confirmation tests and projected lifetimes were correlated with measured interbar voltages. Lifetime expectancy for the sidewall Z-bar elements should be sufficient for the requirements of the program.

Work was also conducted to identify and rectify a potential channel design problem relating to hairline cracks in the caps of the tungsten on tungsten-copper sidewall elements.

CURRENT CONSOLIDATION SUBSYSTEM DESIGN AND FABRICATION (SECTION 6)

Work during this quarter focused on the construction of the full-scale Current Consolidation Subsystem. All major long lead components have been received. These components were tested to assure conformity to the procurement requirements before installation into the system. Assembly of the lower

portion of the power cabinets is complete. Assembly of all SCR and GTO-type switch modules has also been completed. Preliminary testing of a complete consolidation circuit was successfully conducted this reporting period.

CDIF TESTING (SECTION 7)

The primary objective of the test activities this quarter was to checkout the operation of the continuous slag rejection system. Other secondary objectives were to look at the effect of seed sweeps, to evaluate different slag tank vent configurations, to recalibrate the Endress + Hauser coal flow meters, and to run a test with fine coal. A total of 31.7 thermal hours were accumulated during this period. There were no power hours during this quarter due the failure of the magnet system as reported in the last quarterly.

The corrosion test coupons, installed in the transition section between the precombustor and slagging stage, were tested. The results of these tests led to the deletion of the post-test heater loop planned as part of the LPCS.

The precombustor combustion can, S/N 02, was removed and inspected. This can had an Inconel plasma-sprayed lining (as opposed to S/N 01 which had Inconel cladding) with grooves cut into the surface to simulate prototypical sections. Upon removal and inspection, several spalled liner sections were noted where the plasma-sprayed material had been lost. This rough surface contributed to slag adherence which led to fouling. This can was removed from service and the original combustion can reinstalled.

After 250 hours of operation, the oil-fired vitiator chamber and elbow were removed to allow recasting of the refractory material. A new vitiator chamber and elbow were installed in their place. It was also noted that the oil burner had several plugged ports. The burner was removed, ultrasonically cleaned, and reinstalled.

Other hardware activities that occurred during this quarter included:

- 1) Replacement of all "suspect" bolts for the combustor.
- 2) Rebuild of the channel to include prototypical coupons.
- 3) Modification of the slag tank vent line to support test objectives.
- 4) Modification of the slag grinder and funnel to support off-line grinder optimization testing.

MODELING AND PERFORMANCE ANALYSIS ACTIVITIES (SECTION 8)

In the combustion subsystem, efforts were focused on understanding and improving the current levels of slag recovery, and evaluating slag tank and precombustor operation for the purpose of ensuring reliable, long duration operation of each of these components.

A large amount of sidewall data was reviewed in support of the CDIF. This data was used to determine the sensitivity of sidewall behavior to different influences including the effects of different iron oxide rates and generator loading.

TTIRC (SECTION 9)

A meeting of the General Committee of the TTIRC was held on June 17, 1991 at the OMNI Royal Orleans Hotel in New Orleans. The meeting preceded the SEAM conference. Business included discussions regarding seed regeneration options and economics, Western coal test plans at the CFFF, channel power management for the ITC, utility issues and concerns for MHD commercialization, and an update on the Clean Coal Technology proposal activities.

SCHEDULE

The overall schedule for the ITC project is shown on the following pages.

MHD ITC Project
Revised Schedule (Continued)
 August 26, 1991

1. INTRODUCTION

The Magnetohydrodynamics (MHD) Integrated Topping Cycle (ITC) Project represents the culmination of the proof-of-concept (POC) development stage in the U.S. Department of Energy (DOE) program to advance MHD technology to early commercial development stage utility power applications. The project is a joint effort, combining the skills of three topping cycle component developers: TRW, Avco/TDS, and Westinghouse. TRW, the prime contractor and system integrator, is responsible for the 50 thermal megawatt (50 MW_t) slagging coal combustion subsystem. Avco/TDS is responsible for the MHD channel subsystem (nozzle, channel, diffuser, and power conditioning circuits), and Westinghouse is responsible for the current consolidation subsystem.

The ITC Project will advance the state-of-the-art in MHD power systems with the design, construction, and integrated testing of 50 MW_t power train components which are prototypical of the equipment that will be used in an early commercial scale MHD utility retrofit. Long duration testing of the integrated power train at the Component Development and Integration Facility (CDIF) in Butte, Montana will be performed, so that by the early 1990's, an engineering data base on the reliability, availability, maintainability and performance of the system will be available to allow scaleup of the prototypical designs to the next development level.

Ten tasks comprise the ITC Project.

- Task 1 - Systems Engineering Studies
- Task 2 - 50 MW_t Combustor Design, Fabrication, and Shipment
- Task 3 - 50 MW_t Channel Design, Fabrication, and Shipment
- Task 4 - Diffuser Design, Fabrication, and Shipment
- Task 5 - Power Conditioning Design, Fabrication, and Shipment
- Task 6 - Test Engineering Activities at the CDIF
- Task 7 - Hardware Repair/Replacement
- Task 8 - MHD Technology Transfer/Integration
- Task 9 - Quality Assurance
- Task 10 - Integrated Project Management

This Sixteenth Quarterly Technical Progress Report covers the period May 1, 1991 to July 31, 1991. The report is organized into sections which roughly follow the above task structure. The first section is this introduction. Section 2 contains a concise description of the contract tasks to be performed and their objectives. Section 3 summarizes the systems engineering activities in Subtask 1.1. Sections 4 through 7 summarize progress on the combustion subsystem (Task 2), channel subsystem (Tasks 3 and 4), and current consolidation subsystem (Task 5) for this reporting period, and discuss testing at the CDIF (Subtasks 1.2 and 6.3). Section 8 reports the results of ongoing power train performance analyses which are part of Subtask 1.3. Activities of the Technology Transfer, Integration and Review Committee (TTIRC) are reported in Section 9. Planned activities during the next reporting period are summarized in Section 10. Section 11 is a brief summary of the work performed during the quarter, and Section 12 is the distribution list for this report.

2. PROJECT DESCRIPTION

The overall objective of the project is to design and construct prototypical hardware for an integrated MHD topping cycle, and conduct long duration proof-of-concept tests of the integrated system at the U.S. DOE Component Development and Integration Facility (CDIF) in Butte, Montana. The results of the long duration tests will augment the existing engineering design data base on MHD power train reliability, availability, maintainability, and performance, and will serve as a basis for scaling up the topping cycle design to the next level of development, an early commercial scale power plant retrofit.

The components of the MHD power train to be designed, fabricated, and tested include:

- A slagging coal combustor with a rated capacity of 50 MW thermal input, capable of operation with an Eastern (Illinois No. 6) or Western (Montana Rosebud) coal,
- A segmented supersonic nozzle,
- A supersonic MHD channel capable of generating at least 1.5 MW of electrical power,
- A segmented supersonic diffuser section to interface the channel with existing facility quench and exhaust systems,
- A complete set of current control circuits for local diagonal current control along the channel, and
- A set of current consolidation circuits to interface the channel with the existing facility inverter.

Specific objectives of the ten contract tasks are shown in Table 2-1. The overall approach to meeting these objectives is to: 1) utilize the design and operational experience gained from workhorse hardware to design and construct prototypical hardware, 2) conduct design verification tests on the prototypical hardware, and 3) integrate and operate the components for 1000 hours as a complete power train at the CDIF. At the current stage of the project, the technical approach is focusing on item (1) above. Fabrication of prototypical hardware for the combustion, channel, and current consolidation subsystems continued this quarter. The preliminary design review for the low pressure cooling system was held and the order for long lead procurements was placed. Systems engineering disciplines are ensuring compatibility of each of the prototypical subsystems with the overall topping cycle system as well as with the CDIF where they eventually will be integrated. Finally, the TTIRC is disseminating information on the POC program and airing the major integration issues involved in retrofitting an existing power plant so as to permit utilities, the potential future users of the technology, to assume an active role in the U.S. MHD program.

TABLE 2-1. MHD ITC TASK OBJECTIVES

SYSTEMS ENGINEERING STUDIES (TASK 1)	<p>Perform power train/facility integration activities to ensure compatibility of topping cycle components with the existing test bay at the CDIF</p> <p>Define system level requirements and specifications for the integrated topping cycle power train</p> <p>Provide test planning and performance data analysis support for CDIF power train testing</p>
PROTOTYPICAL 50 MW _t COMBUSTOR DESIGN, FABRICATION, AND SHIPMENT (TASK 2)	<p>Design, fabricate and deliver to the CDIF a prototypical coal-fired combustor for the integrated topping cycle power train</p> <p>Conduct testing in support of the prototypical design effort or to evaluate the risks and benefits of proceeding to the development of an early commercial scale retrofit MHD power plant</p>
PROTOTYPICAL 50 MW _t CHANNEL (TASK 3)	<p>Design, fabricate and deliver to the CDIF a prototypical MHD channel (including the inlet nozzle and diagonal current controls) for the integrated topping cycle power train</p> <p>Conduct testing in support of the prototypical design effort or to evaluate the risks and benefits of proceeding to the development of an early commercial scale retrofit MHD power plant</p>
DIFFUSER (TASK 4)	<p>Design, fabricate and deliver to the CDIF a diffuser section for the integrated topping cycle power train</p>
POWER CONDITIONING AND INVERTER (TASK 5)	<p>Design, fabricate and deliver to the CDIF current consolidation circuits for the prototypical channel</p>
TEST ENGINEERING ACTIVITIES AT THE CDIF (TASK 6)	<p>Provide to CDIF personnel technical direction and guidance for the installation, checkout and testing of CDIF MHD power train components and appropriate auxiliary equipment</p>
HARDWARE REPAIR/REPLACEMENT (TASK 7)	<p>Provide for the repair or replacement of power train components that show excessive wear, are damaged, or fail as a result of operations and testing at the CDIF</p>
CHARTER AND PARTICIPATE IN AN MHD TECHNOLOGY TRANSFER, INTEGRATION AND REVIEW COMMITTEE (TASK 8)	<p>Organize, charter and co-chair a committee that will permit potential users of MHD technology in the private sector to assume an active role in the MHD Program</p> <p>Review and integrate POC program schedules and integration issues and provide for technology transfer to potential future users</p>
QUALITY ASSURANCE (TASK 9)	<p>Prepare and implement a plan to assure that prototypical power train components are manufactured per the approved design</p>
INTEGRATED PROJECT MANAGEMENT (TASK 10)	<p>Provide for overall technical, programmatic and subcontract management for the project</p>

3. SYSTEMS ENGINEERING (TASK 1)

Systems engineering activities related to the power train integration and testing at the CDIF are discussed in this section. These activities comprise Subtask 1.1 of the ITC Project.

A principal objective of the systems engineering task is to focus the program's technical effort so that the subsystems designed and built for the topping cycle not only perform well by themselves, but also perform well when interconnected and integrated into the 50 MW_t power train at the CDIF. The integrated topping cycle system must be prototypical, and it must be designed to operate at conditions which closely approximate the operating state of a 250 MW_t retrofit power plant.

To attain these objectives, systems engineering studies are being performed on specific issues as they arise, and systems engineering documentation is being developed and maintained current to provide a consistent basis for the design, fabrication and testing of the prototypical power train. The status of the systems engineering documentation for the project is reported below.

3.1 SYSTEM/SUBSYSTEM DOCUMENTATION

Requirements, technical criteria, specifications and interfaces for the power train hardware are being documented to insure that Statement of Work requirements are met and that the subsystems designed and built for the power train are compatible with each other and with the test facility at the CDIF.

3.1.1 Interface Documentation

During the last quarter, the interface document was released for review. Based on the comments received from this review, the document is in the process of being updated. One major change is the addition of an instrumentation list which includes the name of the measured element, the DAS name, instrument type, nominal operating point, the range and accuracy of the instrument, the alarm and trip points, cross-references to the interface ID number, and reference to the appropriate flow diagrams. Additionally, this table identifies all of the instrumentation that requires electrical isolation. Although the instruments and their locations are often not actual interfaces, this document serves as a good vehicle to provide this information.

The completion of these changes to the document are expected by the middle of next quarter. When this document is completed and all signatures gathered, the Interface Document will be released through the Configuration and Data Management (CADM) Office and will be a controlled document that is part of our configuration control.

3.1.2 Channel Requirements Document

The ITC project team decided to publish a new document titled the "Channel Requirements Document" which would pull together, under one cover, all of the requirements that the channel subsystem would place on the CDIF. Work on this document began in April and was completed early this quarter.

This document contains all of the channel physical dimensions, the cable and manifold layouts, the requirements on the High Voltage Room, and the maximum number of electrodes in the PTO region, the mid-channel region, and the transition region. It specifies the nozzle and diffuser electrical layout and identifies the maximum requirements for bleed resistors in these areas. The document also clearly specifies the instrumentation and metering that will be required for the channel subsystem.

A meeting at the CDIF, with MSE, Avco/TDS, and TRW in attendance, was held at the end of May to discuss and review the document for completeness and the impact of the requirements on the CDIF. Based on the review meeting, the document was revised and reissued, as Revision A, in mid-June. This document forms the basis for the HVR modification design (for the 1A4 channel) which was kicked off at the end of this quarter.

3.1.3 Integrated Schedule Review

During this quarter, a detailed look was taken at the schedules for all of the parties involved in the POC testing: 1) MSE, to understand the facility modifications and available test time; 2) TRW, to look at the manufacturing and delivery schedules for the combustion subsystem and the LPCS; 3) Avco/TDS, to look at the channel manufacturing and delivery schedule; and 4) Westinghouse, for the current consolidation manufacturing and delivery schedule. The testing requested by the component developers was also included in the schedule review. These schedules were integrated to assess the status of the entire program. A review meeting, chaired by DOE, was held during the SEAM conference in mid-June.

The schedule issues will continue to be addressed in the coming months to ensure that these schedules do not slip and impact the baseline scheduled start of the duration testing. A weekly telecon between TRW and MSE has been established to allow continual conversation between the component developers and MSE to ensure that all issues are addressed as they surface, to provide the maximum amount of time to prepare work-arounds, and to ensure that these issues do not become problems which could jeopardize the schedule.

3.1.4 Symposium on the Engineering Aspects of Magnetohydrodynamics

The annual Symposium on the Engineering Aspects of Magnetohydrodynamics (SEAM) conference was held from June 18th to the 20th. Several project personnel attended the conference to act as session chairpersons and present their papers.

4. COMBUSTION SUBSYSTEM DESIGN AND FABRICATION (TASK 2)

Task 2 combustion subsystem design support engineering and prototypical design activities are discussed in this section. Three subtasks comprise Task 2 of the ITC project: Subtask 2.1, prototypical combustor design; Subtask 2.2, prototypical combustor fabrication and assembly; and Subtask 2.3, prototypical combustor shipment.

During this quarterly reporting period, the efforts were concentrated on Subtasks 2.1 and 2.2. The 2.1 subtask encompasses design support engineering and testing, as well as the actual design of prototypical combustor hardware, and procurement specification development for the low pressure cooling subsystem (LPCS). The 2.2 subtask encompasses the combustor and LPCS fabrication and assembly.

Subtask 2.1 was originally comprised of five elements:

- Subtask 2.1.1, Design confirmation testing at TRW. This subtask has been completed and the results have been reported.
- Subtask 2.1.2, Wall construction evaluations. Also completed and the results reported.
- Subtask 2.1.3, Design of prototypical combustor.
- Subtask 2.1.4, Low pressure oxidant second stage testing and design. This subtask was deleted from the program.
- Subtask 2.1.5, 20 MW_t combustor/channel characterization. Also completed and the results reported.

Subtask 2.2 includes the following elements:

- Subtask 2.2.1, Component fabrication and assembly.
- Subtask 2.2.2, Hot fire DVT testing at TRW. This subtask was deleted from the program.

Section 4.1 titled Combustion Subsystem Design Activities includes elements of Subtask 2.1.3.

Section 4.2 titled Combustion Subsystem Manufacturing includes elements of Subtask 2.2.1.

4.1 COMBUSTION SUBSYSTEM DESIGN ACTIVITIES (SUBTASK 2.1.3)

As a part of the combustion subsystem design development, the following activities occurred during this reporting period:

- Low temperature corrosion protection of the cooling panel backside was finalized and the dryout part of the low pressure cooling system (LPCS) was eliminated.
- Design of assembly and shipping fixtures was completed.
- Design of the combustor manifolds is in progress.
- Manufacturing processes and welding fixtures were finalized.

4.1.1 Low Temperature Corrosion Issues

The following main conclusions regarding low temperature corrosion protection of the low alloy steel components were reported in the previous (15th) Quarterly Report:

- The combustor steady-state cooling water temperature shall be limited to 110°F to protect RTV31 which fills the gap between the cooling panel and pressure shell.
- The cooling panel edges and backsides shall have corrosion protection.
- A 200°F cooling water dryout loop shall be used to minimize downtime corrosion.

The main reason for the 200°F dryout loop was that a path allowing condensation of the corrosive agents on the panel backside may exist. A panel dryout cycle would appear to be attractive for this situation. However, the dryout should be performed in such a way that it will not damage RTV31.

A brief literature review has revealed that virtually every acid resistant protective coating is extremely sensitive to breakdown at elevated temperatures. The worst acid actor is aqua regia (50% HNO₃ - 50% H₂SO₄); nitric acid follows with sulfuric acid being the "least" energetic. The RTV class of synthetic rubbers deteriorates rapidly above 150°F for combinations of the above acids. It was decided that while a panel dryout cycle may achieve the desired result of removing the presence of acid corrosion, it may have the synergistic effect of causing non-repairable damage to RTV31 and other possible protective coatings. Therefore, it was decided to eliminate the 200°F dryout loop from the LPCS and implement alternate operational procedures for drying out the combustor. A new procedure for corrosion protection of the panel backside with RTV coating has been developed. Important features of the procedure are:

- Grit blast and clean panel backside.
- Apply GESS4004 Silicone Primer, allow to cure for 2 hours.
- Apply a thin layer (0.025 to 0.050 inch thick) of RTV88, allow to cure for 18 hours.
- Install cooling panels in pressure shell and fill the remaining gap between the panels and shell with RTV31.

The process assures a very good bond between the panel and RTV88 which serves as the primary protective coating. It should prevent peeling of the panel edges. The RTV31 layer fills all the remaining space between the panel and pressure shell. Since the panel backside temperature remains below 150°F, a small amount of acid solution which may accumulate in the local gaps between RTV88 and RTV31 should not affect the cooling panel reliability.

4.1.2 Manifolds and Servicing Platform Design

The slagging stage cooling water supply/return manifolds have been designed. They are shown in Figures 4-1 through 4-3. In general, the manifolds are oriented parallel to the slagging stage centerline. There are five supply and seven return manifolds. Each return manifold has a flow meter and a temperature gage which will be monitored during combustor testing. The individual cooling panels are connected to the manifolds via 3/4-inch tubes as shown in Figure 4-4.

If required, any of the panels can be instrumented with a flow meter and a thermocouple. The manifolds will be attached to the pressure shell via brackets (see Figure 4-5) to uniquely position each 3/4-inch tube and simplify the initial assembly and maintenance.

The combustor will have three servicing platforms permanently attached to the combustor support stand. They will serve the slagging stage headend plate, the exit end plate, and the precombustor end plate. The platform layouts were developed and detailed drawings are being prepared.

4.1.3 Fabrication Process Development

The main efforts were to finalize the slagging stage baffle, precombustor transition ring and baffle welding fixtures which would limit the post-weld distortions to approximately the 0.050-inch level. This requirement is very tough for the 36-inch diameter parts. A full size slagging stage baffle blank (Figure 4-6) was fabricated and three 360° covers were welded in place. The blank was tack welded to a thick plate and a special welding schedule was used to minimize distortions. After heat treating and removal from the fixture, the blank residual distortion was 0.025 inch and the supporting plate was distorted by $\approx$ 0.015 inch. A real baffle panel will require almost three times more welded joints and the total deflection may go up to 0.075 inch. Hence, it was decided to further reinforce the welding fixture by making it as a stiff table and providing additional tack welding of the baffle plates to the fixture. A similar fixture will be used for the precombustor transition ring. The fixtures are presently being built.

A stiff fixture (Figure 4-7) was also used to demonstrate that the cooling panel edges and parts of the backside can be overlaid without distorting the panel. After overlaying, distortions were well within acceptable limits (less than 0.020 inch).

Figure 4-1. Manifold Plan View

Figure 4-2. Left Side Elevation (Return Manifolds)

Figure 4-4. Air Inlet Section Plumbing Assembly

END VIEW
ROTATED 90° CCW

Figure 4-5. Air Inlet Section Manifold Supports

Figure 4-6. Full Size Slagging Stage Baffle Blank Welding

Figure 4-7. Panel Attached to Overlaying Welding Fixture

4.1.4 Corrosion Protection During Combustor Manufacturing

As described in the previous quarterly report, special precautions are being implemented to prevent corrosion from forming in the panel cooling passages during the manufacturing and acceptance testing cycle. These include eliminating water contact during manufacturing and applying a two-step corrosion protection procedure following leak, proof and flow testing of the cooling panels.

To obtain a qualitative understanding of how fast and under what conditions corrosion will form on the low alloy steel, several coupons were fabricated and tested. The coupons were subjected to conditions which are typical of those which will be encountered by the cooling panels. From these tests, the following conclusions were drawn:

- 1) Only minor corrosion will form on surfaces subjected to ambient air conditions typical of the combustor assembly area.
- 2) Untreated low alloy steel immersed in water will begin to rust rapidly (< 1 hour).
- 3) Treating the low alloy steel (using the preclean/prefilm process) is effective in preventing rust during subsequent contact with water.
- 4) Purging the water passages with GN₂ following proof/flow tests is more effective than simple draining in preventing corrosion.
- 5) Untreated coupons immersed in the preclean/prefilm solution showed no signs of corrosion after 2 hours.

Based on this final conclusion, the proof and flow procedures were modified to use the preclean/prefilm solution rather than DI water during testing. The dilute (<0.1%) solution will have no effect on the test results and will ensure that no corrosion of the cooling passages is formed during the tests.

4.2 COMBUSTION SUBSYSTEM MANUFACTURING (SUBTASK 2.2.1)

The prototypical combustor manufacturing activities are summarized in Section 4.2.1, and the status of low pressure cooling system procurement is provided in Section 4.2.2.

4.2.1 Prototypical Combustor Manufacturing

Fabrication of all the cooling panel assemblies continued during this reporting period. The first four flat panels (Figure 4-8) for the slagging stage exit section have been received and accepted following leak and proof pressure testing along with flow calibration testing. The results of flow tests were well within the predictable range. Surface grooving and gun drilling of other panels continued on the curved shaped panels. However, some delay was experienced as the result of the hole drift during the gun drilling operations. This has been corrected with a change in the tooling setup procedure. A revised delivery manufacturing schedule is currently being formulated to minimize impact on deliveries. An alternate shop is also being evaluated to off-load some of the panel work if it becomes necessary to meet the schedule. The final two panel blanks with Inconel overlay are scheduled to be delivered by the supplier to the ultrasonic inspection vendor the first week in August.

The precombustor combustion can (Figure 4-9) and the coal injector hot sleeve (Figure 4-10) have been received and successfully leak, proof and flow calibration tested at the TRW facilities. The calibrations for these two items also fell within the predictable limits.

All of the low alloy steel components flow tested to date have been subjected to a corrosion inhibiting process for protection during temporary storage.

The precombustor and slagging stage end plates as well as the coal injector and seed injector adapter plates were also fabricated. The coal injector adaptor cooling panels were machined and the covers were welded in place. Manufacturing of the other end plate cooling panels is in agreement with the manufacturing schedule.

SIDE VIEW

END VIEW

Figure 4-8. Flat Exit Section Cooling Panels

Figure 4-9. Precombustor Combustion Can

Figure 4-10. Coal Injector Hot Sleeve

Fabrication of the combustor pressure shells is in progress. The precombustor cylindrical shell manufacturing is close to completion. The only unfinished items are welding of the diagnostic tubes and the PC combustion can supports. The precombustor transition shell welding was completed as well as welding of the slagging stage air inlet and exit sections. Final machining of the sections is in progress. The slag dump shell was welded to the forged saddle, the welds were x-ray inspected, and preliminary machining was completed. All manufacturing issues related to fitting in the slag rejector domes and welding the domes to the slag dump shell were successfully resolved and a control fit check was performed. After welding these domes to the slag dump shell, the section will go into final machining. Most of the shell machining will be completed in August and the acceptance proof and leak tests will be performed in September.

It is anticipated that the exit section will be delivered by mid-September and the balance of the pressure shell sections by the end of September.

Purchase orders for the precombustor baffle and transition ring were placed, shop planning was approved and manufacturing begun. During the preparation of the weld coupons, it became apparent that additional tooling was required to hold the hardware during machining as well as the welding phases. This tooling was designed and is now being manufactured. During early stages of the flow passage groove machining, it was discovered that the grooves must be machined in stages rather than in a one step milling operation. The staged machining significantly reduced the tool wear and minimized baffle and transition plate distortion. These problems and resolutions were also applicable to the slagging stage baffle plates and end plate cooling panels.

Purchase orders for the balance of assembly and shipping fixtures were placed. The air inlet and slag dump assembly fixtures were fabricated.

The manufacture of second stage hardware continued. After the brazing of the stainless steel liners to the copper frames, it was discovered that voids exceeding permissible limits in the bond were present in some of the frames. They were discovered during a C-scan inspection process. A complete investigation of the step-by-step process (the tooling, materials, handling and oven instrumentation and controls) is being conducted. In addition, several full size coupons were brazed while varying various parameters. To date, the exact answer to the problem has not been determined. Initial ideas that the root causes may be the liner flatness surface finish and nonuniform clamping proved to be wrong. It was found that most of the non-bonding takes place on the copper side of the brazed joint. A substantial migration of silver between the copper grain boundaries is present. It was proposed to prevent the silver diffusion by nickel plating the copper frame in addition to nickel plating the stainless steel liner. Specimens will be prepared and will be tested shortly. Other possible alternate brazing schemes are also being considered.

Procurement of assembly hardware continued. This included gaskets, nuts, bolts, etc., as well as all the valves, manifolds, headers and special fittings. It is anticipated that all this hardware will be received during the next two months.

4.2.2 Low Pressure Cooling Subsystem Procurement

During this reporting period, the following tasks were completed as part of the Low Pressure Cooling Subsystem (LPCS) procurement:

- The LPCS vendor, Ellis & Watts, was placed under subcontract on 14 May 1991.
- A Conceptual Design Review of the LPCS design was held at Ellis & Watts on 29 May 1991.
- The LPCS equipment specification was modified to eliminate the 2000°F dryout capability.
- Work on the LPCS detailed design continued, with a Final Design Review scheduled for 13 August 1991.
- TRW approved the purchase of several long lead items to ensure adherence to the LPCS delivery schedule.

As described in the previous quarterly report, the LPCS will supply low pressure (300 psi), controlled chemistry water for cooling the POC combustion subsystem hardware. The skid-mounted LPCS is being fabricated by Ellis & Watts of Batavia, OH, and will be delivered to the CDIF in December 1991.

An informal review of the Ellis & Watts design concept for the LPCS was held in late May. The preliminary piping and instrumentation schematic was reviewed, as was the overall equipment layout. Elevation and plan views of the LPCS skid are shown in Figures 4-11 and 4-12, respectively. The main tank is cylindrical with a 5-foot diameter and 15.5-foot overall height, including supports, and holds 1500 gallons. Two 750 GPM centrifugal pumps in parallel are used to supply the main flow. A small 150 GPM pump is used to circulate the water between tests to maintain the water chemistry within specification. Separate filters are used for deionization and oxygen removal. The heat exchanger is of the plate-and-frame type, which results in a very compact unit.

To maintain the LPCS delivery schedule, Ellis & Watts have requested and received approval from TRW for the purchase of several long lead items, including the tank, pumps, heat exchanger, purity loop and safety valves.

All action items from the Conceptual Design Review have been resolved, and the detailed design effort is well underway, with the Final Design Review scheduled for 13 August 1991. The review will cover the final equipment layout, flow schematic, instrumentation, control and electrical schematics, and the interface control drawing which provides details of the connections to the CDIF. The review will be attended by both MSE and TRW personnel.

Figure 4-11. LPCS Equipment Layout (Elevation View)

Figure 4-12. LPCS Equipment Layout (Plan View)

5. PROTOTYPICAL CHANNEL DESIGN (TASK 3)

During this reporting period, work has been initiated on the fabrication of channel related prototypical hardware. The cathode wall fabrication is complete, the sidewall element fabrication has been initiated and anode procurements have begun. A summary of the ongoing channel design activities is presented in Section 5.1. The results of sidewall design confirmation tests conducted at the CDIF on the 1A1 channel are presented in Section 5.2.

Work was also conducted to identify and rectify a potential channel design problem relating to hairline cracks in the tungsten caps of the tungsten on tungsten-copper sidewall elements. Cracks along the slag attachment groove were discovered in some of the sidewall material coupons tested at the CDIF. The problem was attributed to stresses induced in the caps during the braze process and is being investigated as described in Section 5.3.

The status of channel manufacturing is discussed in Section 5.4.

5.1 1A4 CHANNEL DESIGN

5.1.1 Summary

The final design of the MHD channel for the Integrated Topping Cycle Program proof-of-concept 1000-hour test was completed in the previous reporting period. The channel, designated as the 1A4, is a linear supersonic diagonally loaded MHD generator. The insulating sidewalls incorporate segmented diagonal bar construction of constant height. The channel is designed to be capable of 1.5 MW_e power output and a lifetime of 2000 hours. The essential design elements were summarized, along with an overview of the fabrication methodology, in previous quarterly reports.

Results from the Avco/TDS Mark VII MHD test facility used to compare the electrical characteristics of straight- and Z-bar sidewalls and to analyze sidewall behavior in order to provide confirmation for the prototypical sidewall design are reported herein.

5.1.2 Electrical Characteristics of Segmented Bar Sidewalls

The barewall sidewall comparison tests were carried out for several reasons. First, the interbar fault power comparisons between the various sidewall configurations can be accomplished more easily with the barewall data. This is because the data is not affected by internal slag shorting. Secondly, the barewall data are not influenced by the effects of slag-induced cathode nonuniformities, which cause sidewall voltage maldistributions and complicate sidewall performance comparisons.

The test results showed that the wear-inducing electrical stresses are much lower and more uniformly distributed in the "Z" configuration than in the straight-bar design.

5.1.2.1 Introduction

A segmented bar sidewall design was selected for the MHD Integrated Topping Cycle (ITC) prototypical generator. The sidewall bars are arranged in a Z-shaped pattern in order to follow plasma equipotential lines more closely than is possible with a conventional straight-bar design. This is desirable because misalignment of the bars with the plasma equipotential can result in excessive wear on the sidewall elements.

Generator tests have been carried out in the Mark VII to confirm the ITC prototypical sidewall design. Several of the tests were undertaken to directly compare the electrical characteristics of the straight- and Z-bar sidewalls, while other tests (duration tests) were carried out to confirm the detailed design of the ITC prototypical sidewalls. Descriptions of the slagging sidewall comparison tests and the details of the sidewall design confirmation tests were reported in an earlier quarterly report (Reference 5-1). A subsequent test series was carried out to compare the electrical characteristics of sidewalls under barewall conditions. The results of these barewall tests are reported in this report.

Although the barewall generator operating condition is not representative of the ITC proof-of-concept tests, it was investigated in the Mark VII for several reasons. First, the appearance of slag-induced cathode nonuniformities results in sidewall voltage maldistributions which complicate sidewall performance comparisons. Second, interbar fault power comparisons between the various sidewall configurations can be accomplished more easily with barewall data. The fault power across a particular sidewall insulator gap is estimated by short-circuiting two adjacent wall elements and measuring the resulting short-circuit current. When the sidewalls are slagged, a fraction of the interbar current flows across the gap through the slag layer. This current path causes inaccurate measurement of the interbar short-circuit current. Also, for slagged walls, the values of the interbar currents are often unsteady and are not reproducible due to changing conditions of the slag coverage. Thus, barewall results are included in our sidewall investigation since the qualitative performance trends of the various sidewall configurations also apply under slagging conditions.

5.1.2.2 Barewall Comparison Tests

A workhorse generator channel was used for the sidewall comparison tests. Figure 5-1 shows layouts of the two sidewalls at the locations where the interbar voltage measurements were made. The right sidewall was configured with straight bars while the left wall had the Z-bar configuration. Arrangements were made to accommodate two different bar segmentation patterns, consisting of 3- and 4-segment bar rows, on each of the sidewalls. The terminology for the different bar elements within a row of diagonal bars is included in Figure 5-1. The diagonal bar rows for both sidewalls were inclined at an angle that spanned (overlapped) 9 electrodes. The resulting angle between the straight bars and vertical was approximately 45 degrees, while the slanted portions of the Z-bar rows (i.e., the two center bars) were about 55 degrees from vertical. The 3-segment straight-bar configuration is similar to that presently found in the bar sidewalls of the CDIF 1A1 channel. The 4-segment Z-bar configuration is most like the design proposed for the ITC prototypical sidewalls, except that the latter will have six bar segments in each of the diagonal rows.

The Mark VII generator was configured for diagonal load operation. Current control devices were installed in the external diagonal links, which also had a connection overlap of 9 electrodes to match the angle of the bars. The nominal test conditions were similar to those expected in the ITC proof-of-concept duration tests. The electrical power output, electrode currents, interelectrode voltages, and the sidewall electrical properties were measured at various generator loading conditions.

The different sidewall bar configurations and segmentation patterns which were studied in the barewall tests are shown in Figure 5-2. Configurations A and B are the 4- and 3-segment Z-bar designs; D and E are the straight-bar designs. Configurations C, F and G are obtained by shorting the anode endbars (or end pegs) to the anode midbars of configurations A, D and E, respectively.

The interbar voltage measurements for the different sidewall configurations are compared in Figure 5-3. The interbar voltages are those across the anode endbar-to-downstream anode gaps, and the gap voltages in the region of the overlapping midbars (i.e., cathode sidebar-to-upstream midbar gap, cathode midbar-to-upstream anode midbar, etc.). These voltages are compared because very high interbar voltages were measured in these regions on the CDIF straight-bar sidewalls and this is also where material wear is often observed (Reference 5-1). It is clear that the maximum voltages across these critical gaps can be greatly reduced by utilizing a Z-bar configuration and by increasing the bar segmentation. Reduction of these high voltages decreases the likelihood for interbar arcing and diminishes the driving force for electrochemical corrosion.

The magnitudes and directions of the bar currents for a few selected sidebars are also shown in Figure 5-3. These are the currents that normally circulate within the sidebars under nominal Mark VII generator operating conditions. The currents are driven by the electric potential gradients resulting from any misalignments between the sidebar orientation and the plasma equipotential direction. These internal bar currents were determined by measuring the appropriate interbar shorting currents. For example, the bar

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Figure 5-1. Layouts of the Sidewalls for the Mark VII Bar-Wall Comparison Tests

Figure 5-2. Sidewall Configurations. Mark VII Clean Fueled Sidewall Comparison Tests

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Figure 5-3. Measured Voltage Distributions and Bar Currents. Mark VII Clean Fueled Sidewall Comparison Tests

currents flowing in the long midbars of configuration B were determined by shorting the anode and cathode midbars of configuration A and measuring the shorting currents. Similarly, the bar currents in the anode sidebars of configuration G were determined by shorting the anode sidebars and midbars of configuration E. While only a few of these internal bar current measurements were made during the barewall tests, and they were further limited to the long sidebars, the results of Figure 5-3 suggest that the currents circulating in Z-bar elements are lower than those in the straight bars. The bar currents in the long Z-bar elements are all less than 0.2 A, while those in the long straight bars are all over 0.2 A. This trend implies that the Z-bar orientation is better matched to the plasma equipotential direction.

Another important parameter to consider in the sidewall comparison is the interbar fault power. The fault power depends not only on the gap voltage, but also on the rigidity with which the plasma tends to impose such voltages between adjacent bar elements. The larger the interbar fault power, the greater the potential for sidebar wear and damage. The fault power across a particular gap can be estimated by short-circuiting adjacent bar elements and measuring the resulting short-circuit current. The interbar fault power is proportional to the product of interbar short-circuit current and open circuit voltage. The measured interbar short-circuit currents for the different sidewall configurations are compared in Figure 5-4. The magnitudes of the shorting currents across the anode-to-upstream anode endbar gaps are very high for the straight-bar sidewalls (more than three times higher than for the Z-bar configuration). The short-circuit currents across the cathode sidebar-to-upstream anode sidebar gaps are also large for sidewalls with long cathode sidebars (i.e., configurations E and G). The interbar gaps with large short-circuit currents also have very high interbar voltages, as shown earlier in Figure 5-3. The combination of large interbar short-circuit current and high gap voltage implies a large fault power. The locations of these gaps are precisely where the greatest material wear was observed on the CDIF straight-bar sidewalls (Reference 5-1).

Figure 5-5 compares the measured interbar short-circuit currents in the anode/sidewall corner regions and shows the directions and the current paths of these currents. Several interesting trends can be noted:

- 1) The measured interbar short-circuit currents and the resulting values of fault power are substantially lower for the Z-bar configurations (configuration A and C) than for the straight-bar designs (configuration D and F). This trend suggests that the Z-shaped sidebar orientation is better matched to the plasma equipotential direction in the anode wall region.
- 2) The value of the short-circuit current increased at least three-fold when the length of the anode end bar is increased (compare configuration A versus C). This also resulted in more than three-fold increase in the amount of interbar fault power. A sidewall arrangement similar to configuration C was being considered previously for the 1A4 sidewalls as a method for reducing the anode-sidebar corner gap voltage. As a consequence of this above trend, sidebar configuration C was eliminated from consideration for the baseline 1A4 sidewalls. However, the capability to jumper adjacent sidewall elements in the region is incorporated in the 1A4 design.
- 3) The paths taken by the anode-to-sidebar shorting currents are different for the long Z- and straight-bar configurations (compare configurations C and F). In configuration F, a large fraction of the shorting current (approximately 5.3 A) flows from the anode sidebar and into the gas at a location very near the anode wall, in the anode boundary layer region. By contrast, all of the shorting current in configuration C (approximately 1.6 A) flows to the gas at a location much further away from the anode, closer to the core flow region of the channel. In general, current flows from the sidebar to the gas at the location where the voltage gradient (between the wall and the gas) is the greatest. The fact that very little current flows out of the end bars in the anode wall boundary layer regions (in configurations A and C) suggests that the Z-bars are very well matched to the plasma equipotential lines in these wall corner regions.

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Figure 5-4. Measured Interbar Short-Circuit Currents. Mark VII Clean Fueled Sidewall Comparison Tests

Figure 5-5. Comparison of Shorting Currents in the Anode/Sidewall Corner Regions. Mark VII Clean Fueled Sidewall Comparison Tests

5.1.2.3 Conclusions

Mark VII workhorse channel tests were carried out to compare the electrical characteristics of straight-bar and Z-bar sidewall configurations under barewall operating conditions. The data was collected to supplement the earlier slagging wall measurements. The effects of bar segmentation on the interbar voltage distributions and on the interbar fault power were studied. A review of the measured data resulted in the following conclusions:

- Interbar voltages and circulating bar currents for the new ITC prototypical Z-bar sidewalls will be substantially lower than those for the straight segments of the 1A1 sidewalls.
- The increased bar segmentation on the ITC sidewalls will also reduce the interbar voltage and interbar fault power.
- Z-bar sidewalls reduce the potential for arc breakdowns at the anode/sidewall corner joints.

5.1.3 Packaging

Efficient packaging of hosing, wiring, and manifolds permit the 1A4 channel to readily fit inside the bore of the existing 3 T iron core magnet at the CDIF. As described in the previous reporting period, transfer manifolds are used to provide water connections to the gas-side elements with a minimum of hosing. Manifolds, wires and connectors are held in place with brackets and wire guides eliminating the possibility of crimped hoses or interference with the magnet bore liner. Various packaging schemes of the external components are being evaluated using a full-scale mock-up of the 1A4 channel. The external packaging activities are nearly complete and a photograph of the full-scale mock-up is shown in Figure 5-6.

Figure 5-6. Photograph of Channel Mock-Up

5.2 1A4 DESIGN CONFIRMATION TESTS AT THE CDIF

5.2.1 Introduction

During the previous reporting period, the 1A4 design confirmation tests at the CDIF were completed and the results reported. During this reporting period, sidewall wear data and projected lifetimes were correlated with measured interbar voltages and are reported herein.

Several 1A4-style test coupons were installed in the 1A1 channel (Build No. 1). These elements were tested to confirm that anode, cathode and sidewall element design and material selections would achieve expectations when used in the coal-fired environment of the 1A1 channel. Both primary and secondary element designs, as well as alternative material selections, were evaluated during these tests.

The sidewall elements were subjected to coal-fired plasma conditions during power and nonpower operations. Although the elements were exposed to a corrosive-erosive environment during both types of operation, only those hours where the channel was operated under power were used to estimate lifetimes. The observed life-limiting wear was consistently observed on anodic surfaces which were driven by electric fields established during power operations. Twenty-two hours of coal-fired power generation with 19 hours at prototypical stress levels were accumulated.

5.2.2 Sidewall Z-Bar Element Lifetime Projections

The lifetimes of Z-bar sidewall elements were estimated based on material wear with respect to time exposed to prototypical stress conditions. A 20-hour (power) CDIF test series, consisting of the following runs: 91-CHK-2, 91-MATL-4, 91-MATL-5, 91-MATL-6, and 91-MATL-8, was examined for this purpose.

Two Z-bar sidewall sections were in place at approximately mid-channel on opposite walls. These sections consisted of 12 adjacent diagonal bar frames, with 5 bar elements in each frame. The four middle diagonal frames on each wall were instrumented for interbar voltage measurements. Figure 5-7 illustrates the 1A1 (5 element per frame) sidewall configuration while Figure 5-8 shows the prototypical (6 element per frame) sidewall design which will be used for POC testing. The finer segmentation of the prototypical sidewall design will result in smaller interbar voltages, and hence, lifetimes greater than those projected from the 1A1 data examined here.

The materials tested in these Z-bar sections included solid tungsten-copper (the anode-side endbar and the two upper bar elements) and tungsten-copper with tungsten cap elements (the cathode-side endbar and the lower bar element). Other sidewall designs and material constructions were in place during these tests. However, only the results of the solid tungsten-copper and tungsten capped designs are discussed here since they are the designs proposed for the 1A4.

A map illustrating the observed material wear with typical cross-bar voltages, at critical gap locations, is shown in Figure 5-9. The values of these cross-bar voltages are slightly greater than those expected during POC testing, since the bars tested have less segmentation than the prototypical design. Figure 5-10 presents the sidebar lifetime projections for the studied Z-bar configuration. Most of the cross-bar regions show no observable wear and have long lifetime projections of well over 5000 hours. These elements include: the anode end bars, the cathode end bars, and the anode side bars (see Figure 8-21 for Z-bar nomenclature).

In the row of midbars, wear was apparent on only one element out of 12 elements in that row. Data obtained from the instrumented bar frames indicates that the average cross-bar voltage between midbars and the upstream anode sidebars (see gap 'C' in Figure 5-9) is 70 volts. It would appear that for the most part,

Figure 5-7. Z-Bar Configuration for CDIF-1A1 Channel

Figure 5-8. Z-Bar Sidewall Design CDIF-1A4 Channel

Figure 5-9. 1A1 Z-Bar Sidewall Wear Map with Typical Cross-Bar Voltages

Figure 5-10. Z-Bar Lifetime Projection Summary for CDIF-1A1 Channel

70 volts across this gap will not damage the elements here. However, the single element with wear showing was not in the instrumented region, and may have experienced an abnormally high voltage. A lifetime projection of 2100 hours was calculated for the midbars based on wear showing on that one element (Reference 5-2). This projection could be substantially higher if indeed the wear on that one particular element was abnormal.

Wear was also apparent on the cathode sidebars (with a tungsten cap) (see gap 'D' in Figure 5-9). The cross-bar voltage between the cathode sidebars and the upstream sidebars were observed to be at two distinct average values, either 30 or 60 volts. At the 30 volt threshold, a lifetime projection of well over 5000 hours was calculated. At the 60 volt threshold, the lifetime was projected to be 2200 hours.

For this test series, the Z-bars were instrumented only for voltage measurements. Wear on sidewall bar elements is a function of voltage across a gap and circulating current at that gap. However, during some recent Mark VII tests described in Section 5.1.2.2, both sidewall short circuit currents and voltage data were measured, allowing a more complete profile of sidewall behavior. The results of the present investigation show that the voltage distribution on the sidewall, by remaining fairly constant, imply that the circulating current is constant. Therefore, the material wear which has been attributed to a particular voltage across a gap should be accurate.

The lifetime projections calculated here are based on linear calculations. Past experience has revealed that wear rates are nonlinear so that bar elements deteriorate quickly initially and then stabilize. This presents another reason why the projections herein are conservative. Lifetime expectancy for the sidewall Z-bar elements should be sufficient for the requirements of the program.

5.3 TUNGSTEN CAP CRACKING INVESTIGATION

5.3.1 Background

Several 1A4-style sidewall elements that were installed and tested in the 1A1 channel developed hairline cracks in the gas-side cap along the slag attachment groove. These cracks were in the tungsten cap of the tungsten on tungsten-copper sidewall elements. Both cathode end bars and cathode sidebars experienced cracking of the cap. Preliminary analysis suggests the cracks result from stresses induced by the different thermal expansion rates of the tungsten caps and the tungsten-copper base materials during brazing. Thus, proceeding with the fabrication of the Zone 1 elements requires both an understanding of the problem root cause and the successful implementation of a corrective action. The activities undertaken are outlined in the following sections.

5.3.2 Design

The 1A4 channel Zone 1 Z-bar elements were comprised of a 3/8-inch thick tungsten cap vacuum brazed onto a tungsten-copper (press-sintered, 75% tungsten-25% copper by weight) base using a gold-nickel braze alloy. Lead free naval brass water tubes and tungsten-copper plugs are torch brazed using B505 braze alloy and B-1 flux. A layout of the sidewall is shown in Figure 5-11. The Zone 1 elements are the two rows adjacent to the cathode wall. A cross-section of the sidewall design is illustrated in Figure 5-12.

The tungsten capping along the bottom two rows of the sidewall (Zone 1) protects the gas-side surface in the event that slag polarization induced high voltage gaps occur along the cathode wall. The tungsten cap provides resistance to the resulting electrochemical and arc erosion processes. The base material is a press-sintered tungsten-copper composite. Tungsten-copper is utilized because inter-element arcing below the primary gas-side capping can occur when cathode wall high voltage gaps are present. Tungsten-copper being far more resistant to erosion than copper was chosen for this purpose.

5.3.3 Root Cause Investigation

Close examination of the 1A4-style tungsten caps on tungsten-copper bases installed in the CDIF 1A1 channel showed hairline cracks along the direction of the slag attachment groove. The cracking initiates in

Figure 5-11. 1A4 Channel Sidewall Gas-Side Material Zone Layout

Figure 5-12. 1A4 Sidewall Z-Bar Elements

the base of the slag attachment groove and propagates down toward the tungsten-copper base. Both cathode end bars and cathode sidebars experienced some percentage of cap cracking. Figure 5-13 show an illustration of a typical hairline crack. No such cracks were observed in the tungsten on copper designs or the solid tungsten-copper designs (Zones 2 and 3 of Figure 5-12, respectively). In addition, no cracks were observed in the 1A4-style cathode electrodes which are comprised of tungsten caps on copper bases. Preliminary analysis suggested the cracks are due to different thermal expansion rates of the tungsten cap and the tungsten-copper base materials. The different thermal expansions induce stresses in the tungsten cap during the braze process which cause cracking in the orientation of the material laminations. Careful post-fabrication inspections and bench top thermal cycling tests were conducted which support these preliminary findings. Both the cap/base vacuum braze step and water tube torch braze can induce a signature (precursor to a crack) which is then exacerbated by the normal channel thermal cycles during MHD testing resulting in a hairline crack. Bench top thermal cycling tests were conducted that also produced similar cracking as that observed in the CDIF test coupons, further supporting the preliminary findings. It has not been determined whether the cracks continue to propagate, enlarge or continue into the tungsten-copper base.

5.3.4 Corrective Action

Action taken to provide a solution to the problem consisted of evaluating alternate designs. Of the several options evaluated, two approaches emerged as the most promising:

- The use of a stress-relief compliant layer between the tungsten cap and tungsten-copper base
- The use of a split tungsten cap (reducing the characteristic dimension in the stress induced direction) through the slag attachment groove

Figure 5-13. Typical Hairline Crack in Tungsten Cap of a Cathode End Bar

Figure 5-14 shows a schematic of the two design options. Plans have been made to test sidebars fabricated with the stress-relief compliant layer at the CDIF (see Section 7.2.2 for details) and in the Mark VII facility. In addition, rigorous in-process manufacturing inspections and post-manufacturing thermal cycling tests are planned on candidate designs. A logic network for these activities is depicted in Figure 5-15.

5.4 1A4 CHANNEL FABRICATION STATUS

The 1A4 channel and diffuser are scheduled to be delivered to the CDIF in May 1992, as indicated in the previous reporting period. Although some changes in the baseline schedule have occurred, no slip in delivery is anticipated. Solutions for the sidewall cap cracking problem, including work around plans, have been formulated and will not impact the May 1992 delivery date. The channel fabrication activities are proceeding on schedule.

The 1A4 nozzle, channel and diffuser fabrication status are shown in Figures 5-16 and 5-17. Completed activities are indicated in black and ongoing activities are shown in gray. As shown in these figures, assembly of the cathode wall is complete. A photograph of the cathode elements mounted on the structural plastic wall is shown in Figure 5-18. Also indicated on the schedule, sidewall fabrication activities are underway and procurements for the anode wall are nearly complete. The overall channel fabrication activities remain on schedule.

REFERENCES FOR SECTION 5

- 5-1. TRW, MHD Integrated Topping Cycle, Fourteenth Quarterly Technical Progress Report, November 1990 through January 1991, MHD-ITC-91-411, U.S. Department of Energy Contract No. DE-AC22-87PC90274, Section 5.4.
- 5-2. Textron Defense Systems, MHD ITC Channel Subsystem, Critical Design Review Update, 19 February 1991.

Figure 5-14. Alternate Zone 1 Sidewall Designs

O1M 91.188.11

Figure 5-15. Corrective Action Logic

RM CHANNEL AND DIFFUSER FABRICATION SCHEDULE

Figure 5-16. Channel and Diffuser Fabrication Schedule

Figure 5-18. Photograph of Completed Cathode Wall

6. CURRENT CONSOLIDATION SUBSYSTEM DESIGN AND FABRICATION (TASK 5)

Work during this quarter focused on the construction of the full-scale Current Consolidation Subsystem. All major long lead components have been received. These components were tested to assure conformity to the procurement requirements before installation into the system. Assembly of the lower portion of the power cabinets is complete. Assembly of all SCR and GTO-type switch modules has also been completed. Preliminary testing of a complete consolidation circuit was successfully conducted this reporting period.

6.1 CONSTRUCTION PROGRESS

Figures 6-1 through 6-5 summarize the progress in the construction of the current consolidation subsystem for the anode side as of June 30, 1991. Figure 6-1 shows the two power cabinets which will contain 15 consolidation circuits each. The cabinets have three doors on each side. The center door has been temporarily removed to facilitate construction. Air inlets are located on the left side of the cabinets. The opening above the inlets is for a blower that will be installed later. There are two fans mounted on the right of each cabinet that cannot be seen in the photo. A portion of the input power transformer is shown in the far right of the photo.

Figure 6-2 shows the consolidation filter networks that are installed in the lower portion of the power cabinets. Each filter network consists of two inductors (104 mH and 52 mH) and 6 capacitors (60 μ F each for a total of 360 μ F). All of the filter networks are installed on a base that is insulated from the bottom of the cabinet by twelve 15 kV glastic isolators.

Figure 6-3 shows another view of the filter networks showing the lower I-beam sub-frame that is bolted to the base of the cabinet. The two rectangular openings in the I-beam frame are spaced for forks on a fork-lift truck.

Figure 6-4 shows a completed SCR-style switch module. Fifteen modules of this type and 15 GTO types will be installed in the power cabinets. They will be installed in the power cabinets on a structure of glastic insulating material, as described in the Current Consolidation CDR document. Each of these switch modules primarily consists of 2 power semiconductors mounted on their respective heat sinks, the gate drive boxes for the devices, input fuses, and voltage suppression networks. Figure 6-5 shows a completed GTO-style module, which is very similar to the SCR.

Additional progress has been made since these photos were taken, particularly in the upper areas of the power cabinets. The local and central control racks were received in July.

6.2 MANUFACTURING TEST SUMMARY

All major components from outside vendors are fully tested to insure that they conform to the required specifications. Each component is tested and marked if it conforms to all specifications. To date, all delivered material has met or exceeded the requirements.

6.3 SUBASSEMBLY TEST SUMMARY

Preliminary tests have been conducted on completed SCR and GTO-style consolidation circuits. The purpose of these tests was to verify the basic operation of these circuits. The final control system was not ready when these tests were conducted. The consolidation circuits cannot be tested to their full limits of operation without the control system in place. Once the control system is available, additional testing will be performed.

Since the control system was not available, the circuit was operated under open-loop conditions. No current-loop or voltage-loop regulation was in effect. The firing angle of the devices was varied with a temporary fixture that enabled a limited open-loop control of output voltage range. The circuit was loaded with a 14 ohm, 1.5 KW resistive load bank. The input was connected to the 443 V tap on the power

Figure 6-1. Photo of Anode Power Converter Cabinets

Figure 6-2. Photo of Installed Filter Networks

Figure 6-3. Photo of Lower I-Beam Frame

Figure 6-4. Photo of Completed SCR Switch Module

Figure 6-5. Photo of Completed GTO Switch Module

transformer, which is the maximum voltage. Figure 6-6 shows the test setup for a SCR-type circuit. The test fixture permitted operation at a DC output of around 100 VDC. Both SCR and GTO-type circuits ran successfully under these conditions.

6.4 PLANNED ACTIVITIES

At present, the CDIF is proceeding with modifications in the High Voltage Room (HVR). Since the current consolidation subsystem diode stack is installed in this area, this equipment will be built and delivered early to allow installation in the HVR. Construction and testing of the remainder of the system will also continue.

Figure 6-6. Preliminary Test Circuit Configuration

7. CDIF TESTING

Workhorse power train testing at the CDIF is divided into two phases: 1) Design Verification Testing (DVT) of the coal-fired precombustor (CFPC) and 2) the Confirmation Test Series. During previous reporting periods, the precombustor DVT program was completed and the confirmation testing was initiated. The Confirmation Test Series is focused on confirming the design and performance characteristics of the individual prototypical power train components prior to installation of the entire prototypical power train.

Test activities at the CDIF during the 16th quarter were focused on four test objectives:

- 1) Checkout of the operation of the continuous slag rejection system
- 2) Seed utilization baseline performance characterization
- 3) Calibration of the Endress + Hauser (E+H) coal flow meters that are used to measure and provide feedback control to the precombustor and slagging stage coal flows
- 4) Confirm power train performance characteristics when "coal fines" are reincorporated into the test coal.

A total of 31.7 thermal test hours and 0 electrical hours were accumulated during this reporting period. Electrical test operations had been terminated during the 15th quarter due to the identification of a leak in one of the magnet coils. The leak was not repaired prior to the 16th quarter, and hence, test operations during this reporting period were thermal only.

Hot-fire (thermal) checkout of the continuous slag rejection system was completed during this quarter. During the 15th quarter, the instrumentation and control system installation was completed which enabled continuous, automatic operation of the slag rejection system. One checkout test of 1.6 hours was performed during the 15th quarter. During this reporting period, 7 additional checkout tests were performed (plus 2 special diagnostic tests). These checkout tests confirmed that the system operated reliably in the automatic mode during several continuous cycles. Complete checkout of the system during power operations will be performed during the September 1991 test series.

The remaining test objectives were performed in conjunction with the continuous slag rejection system checkout tests. A recalibration of the two Endress + Hauser meters that are used to measure and control coal flow to the precombustor and main stage of the combustor was performed. Also, one test was conducted utilizing a "blended" coal which contained coal fines from the bag house (~30%) blended with the normal coal grind distribution. In addition, baseline seed utilization performance was characterized at various seed concentration levels in the plasma. Additional characterization will be performed under power conditions during the September 1991 test series. A discussion of these activities is contained in Section 7.1.

The primary hardware activities performed at the CDIF during this reporting period included:

- 1) Evaluation of low temperature acid corrosion on combustion subsystem components
- 2) Confirmation of the improved brazing process utilized on the prototypical channel sidewall elements
- 3) Comparison of the surface characteristics of an Inconel plasma-sprayed surface to that of an Inconel base metal surface
- 4) Optimization of the slag tank grinder, funnel and vent line configuration.

These activities are discussed in detail in Section 7.2.

7.1 WORKHORSE POWER TRAIN TESTING AT THE CDIF (SUBTASK 6.3)

7.1.1 Objectives of Workhorse Test Program

The workhorse test program has three main areas of emphasis at this time:

- 1) To provide operational and test data input to the POC component design such as:
 - Combustor and slag rejector design
 - Current consolidator design
 - Channel design and material verification
- 2) To develop long duration facility operational experience, and
- 3) To provide design verification testing of POC components as follows:
 - Current controls as consolidators
 - Rectangular second stage
 - Continuous slag rejection/removal system

These items comprise the level of effort necessary to provide the ITC program with the confidence for a 2000-hour POC design. However due to an inoperative magnet, these objectives were difficult to meet during this quarter.

7.1.2 Approach

The approach for the workhorse testing includes: 1) longer duration testing (16 to 24 hour electrical tests) to provide design data and longer duration facility experience, and 2) shorter duration testing (4 to 6 hour electrical tests). Shorter duration tests are geared for checkout and verification of the component designs and modifications such as the Phase II slag rejector installation, and operational studies such as the slag tank vent, seed utilization and coal flow meter calibration.

7.1.3 Test Summaries

Nine tests were performed during the 16th quarter. The primary objective of 7 of the tests was the hot-fire checkout of the continuous slag rejection system. In conjunction with these 7 tests, seeding parameters were varied in order to characterize the baseline seed utilization efficiency. Two special diagnostic tests were also performed during this quarter. The first special test was performed in order to determine the accuracy of the coal flow split between the precombustor and the slagging stage. The second was performed in order to evaluate the performance of the power train (slagging behavior, heat loss, slag recovery, etc.) when "coal fines" from the baghouse are reintroduced into the primary coal storage vessel and burned in the combustor. The following sections contain a brief description of these test activities. Additional details on the individual tests are contained in Appendix A. A chronological summary report is presented as Table 7-1. A summary of the test conditions and results is shown in Table 7-2.

7.1.3.1 Continuous Slag Rejector and Seed Utilization Efficiency Test Series

As stated previously, the primary objective of this series of tests was to complete the hot-fire checkout of the continuous slag rejection system. These checkout tests were comprised of seven separate tests. The first two tests (91-SREJ-1 and -2) successfully demonstrated that at zero voltage the automatic cycle of the slag rejection system operated correctly and reliably through several consecutive cycles. The objective of the next three tests (91-SEED-1, -2 and -3) was to demonstrate slag rejection system operation at 900 volts (supplied by the conductivity power supply). Test 91-SEED-02 successfully demonstrated this capability. The final checkout of the system at 6 kV cannot occur until the magnet is operational. These checkout tests are scheduled for September 1991.

Modifications of the existing slag tank gas/water vent were also evaluated during this test series. The gas/water vent serves two primary purposes:

- 1) To vent slag tank gases to the quench duct, and hence, minimize steam generated by the slag quenching process from entering the combustor
- 2) To maintain slag tank water level and temperature within specified limits.

TABLE 7-1. CDIF TESTING - 16TH QUARTER - SUMMARY REPORT

DATE	DESIGNATION	TEST	TIME (MINUTES)			POWER ON MAGNET	POWER AT CONDITION	TEST OBJECTIVE
			OFV	CFPC	CFC			
(1)(2) 04/29/91	91-SREJ-01	C	105	96	87	0	0	SLAG REJECTOR CHECKOUT TEST SERIES - NO MAGNET AVAILABLE
05/01/91	91-SREJ-02	A	340	337	330	0	0	SLAG REJECTOR CHECKOUT TEST SERIES - NO MAGNET AVAILABLE
05/03/91	91-SEED-01	F	93	87	74	0	0	SLAG REJECTOR CHECKOUT TEST SERIES - NO MAGNET AVAILABLE
05/07/91	91-SEED-02	C	283	278	271	0	0	SLAG REJECTOR CHECKOUT TEST SERIES - NO MAGNET AVAILABLE
05/09/91	91-SEED-03	A	278	268	257	0	0	SLAG REJECTOR CHECKOUT TEST SERIES - NO MAGNET AVAILABLE
05/14/91	91-CALB-01	A	57	48	0	0	0	E+H CALIBRATION TEST - NO MAGNET AVAILABLE
05/15/91	91-SREJ-03	A	350	349	344	0	0	SLAG REJECTOR CHECKOUT TEST - NO MAGNET AVAILABLE
05/16/91	91-SREJ-04	A	284	281	276	0	0	SLAG REJECTOR CHECKOUT TEST - NO MAGNET AVAILABLE
05/17/91	91-COAL-01	C	159	156	152	0	0	FINE COAL TEST - NO MAGNET AVAILABLE
(1)			—	—	—			
TOTAL TIME (MINUTES) 16TH QUARTER			1949	1900	1791	0	0	
TOTAL TIME (HOURS) 16TH QUARTER			32.5	31.7	29.9	0.0	0.0	

DOWN-TIME		RANKING	
(1)	PLANNED DOWN TIME	A	MET ALL TEST OBJECTIVES
(2)	CHANNEL AND SECOND STAGE TORN DOWN FOR REVIEW	B	MET MOST TEST OBJECTIVES BUT WAS CONSUMABLES LIMITING AND REQUIRED FOLLOW UP ON NEXT TEST
		C	MET SOME TEST OBJECTIVES
		F	MET NO TEST OBJECTIVES

TABLE 7-2. NON-POWER SLAG REJECTOR CHECKOUT TEST SERIES

SECOND STAGE CONFIGURATION	TESTING OBJECTIVES	TEST RESULTS
<ul style="list-style-type: none"> Normal configuration second stage, LW=2.7, 12-port horz. 0.036-inch diam injection 	<ul style="list-style-type: none"> Primary: <ul style="list-style-type: none"> - Slag rejector checkout Secondary: <ul style="list-style-type: none"> - Seed utilization studies - Slag tank vent studies - Coal fines addition 	<ul style="list-style-type: none"> Automatic cycle of continuous slag rejection system operated successfully for minimum 3 consecutive cycles at 900 volts Elimination of gas vent from slag tank resulted in slag accumulation and eventual plugging of slag funnel. Reinstallation of gas vent eliminated this problem Recalibration of E+H coal flow meters indicated that precombustor coal flow meter was reading artificially high. However, review of the test procedure indicates the recalibration may have been in error and will be repeated Test performed utilizing a coal "blend" which reincorporated "coal fines" into the primary coal storage vessel resulted in excessive slag accumulation with the precombustor. Test shall be repeated

TEST DESIGNATION		ACTUAL TEST CONDITIONS									
Test	Date	N/O	Preheat	PHI1	PHI2	% K	Seed Oxygen Lb/Sec	900V Conduc.	Minutes of Continuous Operation	Slag Funnel Plug	Slag Rejection
91-SREJ-01	04/29/91	0.76	1200/2900	0.55	0.90	1.6	0.25	NO	96	NO	N/A
91-SREJ-02	05/01/91	0.70	1200/2900	0.55	0.90	1.6	0.50	NO	337	NO	38%
91-SEED-01	05/03/91	0.70	1200/2900	0.55	0.90	1.0	0.25	YES	87	YES	N/A
91-SEED-02	05/07/91	0.70	1200/2900	0.55	0.90	1.1, 1.75	0.25	YES	278	YES	?
91-SEED-03	05/09/91	0.70	1200/2900	0.60	0.90	1.1, 1.75, 2.1	0.25	YES	268	YES	49
91-SREJ-03	05/15/91	0.70	1200/2900	0.55	0.90	1.1, 1.75	0.25,0.50	YES	349	NO	41
91-SREJ-04	05/16/91	0.70	1200/2900	0.60	0.90	1.1, 1.7, 2.2	0.25	YES	281	NO	67
91-COAL-01	05/17/91	0.70	1200/Low/High CFPC/Preheat	0.55	0.90	1.7	0.25	YES	156	NO*	40

* Precombustor combustion can fouling noted

During 91-SEED-1, -2 and -3, the vent line configuration was modified in order to eliminate the "gas" vent portion of the vent and to simply utilize a water vent. The purpose of these tests was to determine if the slag tank could operate without a gas vent since the gas vent has historically had problems with plugging. During all three of these test, the slag tank funnel became plugged with large agglomerations of molten slag. These plugs were caused by the elimination of the gas vent. This was confirmed during 91-SREJ-3 and -4 when the gas vent was reinstalled and the system was operated for approximately 11 cumulative hours without any evidence of slag agglomeration in the slag tank funnel. Additional details and analysis of this series of tests is contained in Section 8.2.

The seed utilization efficiency test series was performed in conjunction with the continuous slag rejection system checkout. The primary objective of this series of tests was to obtain baseline performance data on seed utilization efficiency at various seed concentration levels (1.1%, 1.7% and 2.2% K). Conductivity measurements were obtained for steady-state conditions as well as during seed on/off transients. In addition, the impact on conductivity of iron oxide injection, slagging stage equivalence ratio (ϕ_1), and the level of seed carrier gas (oxygen) was evaluated.

7.1.3.2 Special Diagnostic Test Series

Two diagnostic tests were performed during this quarterly reporting period. The objective of the first test, 91-CALB-1, was to reconfigure the coal feed system in such a way that the accuracy of the coal split between the precombustor and the slagging stage could be determined. This test is described in detail in Section 7.2.5.4. In brief, the results of this test indicated that the precombustor coal flow was approximately 20% high and thus the flow control system was adjusted to supply 20% less coal to the precombustor for the remaining tests during the May 1991 test series (91-SREJ-3, -4 and 91-COAL-1). A subsequent review of the test procedure has identified, however, that the calibration test results could be in error and that the original precombustor flowrate may have been accurate. Therefore, additional calibration tests will be performed prior to the September 1991 test series.

The objective of the second diagnostic test, 91-COAL-1, was to verify the performance of the power train (slagging behavior, heat loss, slag recovery, conductivity and/or power) when "coal fines" from the baghouse are reintroduced into the primary coal storage vessel and burned in the combustor. A similar test had been performed in 1989 which had indicated that the overall performance impact was minor, with the exception of slag recovery which was significantly lower. The results of the 91-COAL-1 test did not confirm the previous results. During the 91-COAL-1 test, the heat flux in the coal-fired precombustor components (primarily the combustion can) decayed dramatically within a few minutes of the start of operation and post-test observations identified a large amount of slag accumulation, or fouling, within the precombustor components. Since this slag accumulation had not been observed during the previous "coal fines" test, an investigation was initiated to determine if something, in addition to coal fines, had contributed to the fouling. The results of this investigation are reported in Section 8.3. In brief, it appears that a combination of factors may have led to the rapid slag accumulation during the 91-COAL-1 test. The primary contributing factor appears to be that the precombustor coal flow had been systematically reduced by 20% prior to the test as a result of the 91-CALB-1 test. Since the 91-CALB-1 test results now appear to be in error, it is recommended that the "coal fines" test be repeated after the coal flow meters are recalibrated prior to the September 1991 test series.

7.2 CDIF HARDWARE ACTIVITIES

The primary hardware activities performed at the CDIF during this reporting period included:

- Evaluation of low temperature acid corrosion of combustion subsystem components during both downtime and combustor operation.
- Evaluation of improved channel sidewall element brazing process (coolant tubes/plugs) during thermal cycling.

- Comparison of gas-side surface characteristics of a precombustor combustion chamber which has a plasma-sprayed Inconel 625 surface to that of a chamber which has an Inconel 625 base metal surface.
- Optimization of the slag tank grinder, funnel and vent line configuration.

These activities are discussed in detail in the following sections.

7.2.1 Combustion Subsystem Activities

7.2.1.1 First Stage Filler Replacement - Corrosion Coupon Testing

The low temperature acid corrosion investigation, initiated during the 14th quarter, continued during the 16th quarter. The filler section, the component that transitions from the coal-fired precombustor to the slagging stage, was used to investigate the corrosion. The filler is installed within the slagging stage air inlet section, and hence, simulates the prototypical panel-in-shell configuration. "Coupons" of various materials and/or coatings were tack welded to the backside (cold side) surface of the top and bottom plates of an existing filler section. The coupon layout is shown in Figure 7-1.

Immediately after each test, the bottom plate of the filler was connected to a 200°F cooling water supply in order to "dryout" any condensate on the backside of the plate. The top plate was connected to the city water supply which typically operated at 50°F. Two type K thermocouples, one in the bottom plate and one in the top plate, were utilized to confirm the post-test temperatures of the coupons. These thermocouples also identified that there was a significant flow of hot gases or smoldering of coal/char occurring on the backside surface of the filler. The filler was installed at the end of March and accumulated approximately 30 thermal hours and 1 month of downtime.

The purpose of this evaluation was three-fold:

- 1) To confirm that the prototypical panel design (i.e. Inconel weld overlay on panel sides and RTV encapsulation on backside) provides adequate low temperature corrosion protection for the Proof-of-Concept test program hardware.
- 2) To determine: a) if the majority of the corrosion occurs during actual combustor operation or during downtime, and b) if the proposed 200°F dryout loop minimizes downtime corrosion.
- 3) To evaluate the low temperature corrosion resistance of various materials and/or coatings in the combustor environment.

Observations

Both the top plate and bottom plate backside surfaces were coated with black soot. Several of the tack welds used to attach the coupons to the surface had broken/melted. One of the smaller coupons was missing.

The uncoated low alloy steel coupons (SA387) on both the top and bottom surface were corroded. The coupons were removed from the filler and inspected in detail in order to quantify the corrosion. Visually, there was not much, if any, difference between the uncoated SA387 coupons on the top and bottom surfaces.

There were two sets of low alloy steel coupons with RTV coating on both the top and bottom surfaces. One set utilized a primer in order to promote adherence of the RTV to the low alloy surface, the other set did not. The top surface of the RTV had been protected with a thin metal stainless steel plate. The coupons on the top and bottom surfaces appeared qualitatively different. The thin metal plates protecting the RTV on the bottom surface appeared heat stained and brittle; the majority of the tack welds were easily broken. The RTV on the un-primed coupon was charred and easily crumbled. The metal plates on the top surface appeared to be in an overall better condition (i.e. still somewhat shiny). In both cases, there was a large amount of soot accumulated between the metal plate and the RTV surface. The differences between the primed and un-primed RTV coupons can be summarized as follows:

TOP FILLER PLATE SURFACE COUPON LAYOUT

1	SA387 GRADE 11
2	SA387 GRADE 11
3	SA387 GRADE 11
4	SA387 GRADE 11
5	SA387 GRADE 11
6	SA387 GRADE 11
7	SA387 GRADE 11
8	SA387 GRADE 11
9	SA387 GRADE 11
-
RTV 31 BONDED (PRIMED)
WITH T/C - UNCOATED
RTV 31 (UNPRIMED)
INCONEL 625 WELD OVERLAY
BARE SA387
TEFLON REP
DETONATION GUN LW-16
DETONATION GUN LA-2
BARE SA387

BOTTOM FILLER PLATE SURFACE COUPON LAYOUT

10	SA387 GRADE 11
11	SA387 GRADE 11
12	SA387 GRADE 11
13	SA387 GRADE 11
14	SA387 GRADE 11
15	SA387 GRADE 11
16	SA387 GRADE 11
17	SA387 GRADE 11
18	SA387 GRADE 11
-
RTV 31 BONDED (PRIMED)
WITH T/C - UNCOATED
RTV 31 (UNPRIMED)
INCONEL 625 WELD OVERLAY
BARE SA387
TEFLON REP
DETONATION GUN LW-16
DETONATION GUN LA-2
CHROMIUM PLASMA SPRAY
& SEALER

Figure 7-1. Layout of Coupons on Top and Bottom Plates of Filler

- 1) On both the top and bottom plate, the RTV on the un-primed coupon was easily peeled off. There was a thin layer of soot between the RTV and the low alloy material. The low alloy material appeared in good condition in both cases.
- 2) The RTV could not be removed from the primed surface on the bottom plate. However, on the top plate at least 1/2 of the RTV coating was easily peeled off. It should be noted that the inside surface of the metal cover plate on the top filler plated showed significant heat staining. There was no soot between the RTV and low alloy material. In both cases, the low alloy material appeared to be in good condition.

Preliminary Conclusions

- 1) The RTV appears to provide adequate protection for the low alloy steel. Both primed and un-primed surfaces showed little, if any, corrosion.
- 2) The "priming" of the low alloy surface provided an adherent RTV surface on one surface, but not the other. The reason for this may be that the primer was affected by the high temperatures (i.e. heat staining of the RTV cover plate). Additional development is required in order to provide a consistent primed surface.
- 3) The dryout loop does not appear to minimize corrosion.

The dryout loop was originally proposed as a backup to the primary system, i.e., in the event that the RTV pulled away from the panel in a singular location and the acid had access to that location. Although it was uncertain whether the dryout system would help in all cases, it originally appeared that it would not hurt. If, however, acids remain entrapped between the panels and RTV during the dryout cycle, the acids heated to 250°F may cause damage to the protective RTV coating. A literature review and bench scale tests have identified that RTV in the presence of nitric acid is extremely sensitive to breakdown at temperatures greater than 150°F. Therefore, based on these concerns, it now appears that the dryout loop could "hurt" the primary protection scheme, and hence, the dryout loop has been eliminated from the Low Pressure Cooling System (LPCS).

In order to mitigate the concern of having a localized region where the RTV may pull away from the panel, various RTV primers and surface preparation techniques are being investigated as well as troweling the panel with an initial layer of RTV in order to ensure excellent adherence of the RTV to the panel surface. These results will be discussed in the next quarterly report.

7.2.1.2 Precombustor Combustion Chamber Evaluation

Two different precombustor combustion chambers have been installed at various times at the CDIF. The original chamber, installed in 1989, was constructed utilizing Inconel 625 as the gas-side metal surface. This combustion chamber was replaced in October 1990 with a unit which had a plasma-sprayed Inconel 625 coating (65% nickel, 21% chromium) on the gas-side surface. The plasma-sprayed surface was 0.025 inches thick and had been applied on top of an Inconel 625 base metal in order to provide the capability to machine 0.015-inch deep round-bottom grooves into the gas-side surface without risking damage to the base metal. The grooves, in the axial direction of the chamber, were utilized to simulate a proposed prototypical design which required axial grooves in order to reduce thermal stresses. Initial tests utilizing the plasma-sprayed chamber did not indicate any significant differences in the chamber heat flux characteristics or post-test slagging observation. However, after approximately 10 to 15 hours of operation, the combustion chamber heat flux began to show signs of increased slagging activity. This trend is discussed in more detail in Section 8.3. Following the May 1991 test series, the plasma-sprayed combustion chamber was removed and inspected. The plasma-sprayed surface of the chamber had a very rough surface finish (it had been polished to a 125 finish prior to installation), and there were numerous cracks in the surface layer as well as locations where the coating had spalled off. The slag/char remaining on the chamber surface had a tightly adhering bond with the plasma-sprayed coating. The internal surface

of the original combustion chamber was also inspected and found to be a fairly smooth metal surface. Although slag/char remained on the surface, it had not formed a tightly adhering bond and could be removed much more easily. It is suspected that the rough surface finish on the plasma-sprayed chamber may be promoting slagging of this surface and subsequent slag accumulation and fouling of the downstream precombustor components. Hence, the plasma-sprayed chamber was removed from service and the original chamber reinstalled.

7.2.1.3 Oil-Fired Vitriator Replacement

After 250 hours, the refractory lining of the vitriator chamber assembly showed signs of deterioration, specifically, some erosion of the surface material. Also, due to increased directional impingement of fuel oil from the burner by plugged ports, some gouging of the refractory had occurred. The oil-fired vitriator chamber and elbow (S/N 01) were replaced with the unit which had been in service at TRW's Capistrano test site (S/N 02). Both components (i.e. chamber and elbow) were replaced as a matched set although the elbow assembly at the CDIF did not show any signs of erosion. Set S/N 01 will be re-cast with new refractory in California.

7.2.1.4 Oil Burner

The 8-port oil burner had been in service since March of 1990. The configuration of the oil ports, in relation to the main oil supply chamber, results in oil "cooking" in ports which eventually leads to soot accumulation and plugging of the ports. As many as 4 oil ports have been observed to be plugged at any one time. During test operations, the burner oil ports are usually superficially cleaned with tip cleaners and back flushed with water. After the May 1991 test series, the 8-port oil burner was removed, ultrasonically cleaned at TRW, and subsequently reinstalled at the CDIF.

7.2.1.5 Slag Tank, Grinder, Funnel and Vent Modifications

During the initial checkout tests for the slag rejector system, problems were encountered with slag bridging and blocking of the funnel and grinder. Intermittent problems have also occurred when the slag tank vent line has plugged. The CDIF slag tank vent line consists of a combination gas/water vent line. Several on-line and off-line tests were performed during this period to evaluate different configurations (i.e., separate vents, larger combination vent, no gas vent) to better understand the role of the water and gas vents. Details of these tests and an analysis of the data are presented in Sections 8.2.2 and 8.2.3.

The outcome of the testing and the subsequent data analysis has led to equipment modifications to mitigate these problems in the future. The modifications made to the slag tank during this quarter are summarized as follows:

- 1) Replaced the flat bottom funnel with a 45° sloping funnel
- 2) Installed a 2-inch diameter vent line inside the slag tank (an increase over the previous 1-1/2 inch line)
- 3) Installed a larger diameter vent line cap inside the tank with enhanced cooling design
- 4) Provided a penetration through the slag tank manway for grinder seal pressure equalization.

The effectiveness of these modifications will be further tested during the fall test series and will be reported in future quarterly reports. Details of the slag grinder and funnel optimization are given in Section 7.2.4.

In addition to the above design changes, the method of operating the slag rejector system has been reviewed and recommendations made to improve and automate the process. Appendix B contains the present procedure for slag tank operation and the proposed changes to the procedures and instrumentation.

7.2.1.6 Workhorse CFC Bolt Replacement

The DOE-ID instructions related to H.R. 3000 Fasteners Act requires that all combustor bolts with head markings that were considered "suspect" are to be replaced as they are removed. This was accomplished

during this quarter. Additional bolts were purchased to continue with the replacement of suspect bolts as required.

7.2.2 Channel Activities

During this reporting period, several 1A4 channel-type elements were fabricated for installation in the 1A1 channel at the CDIF. These test coupons are comprised of prototypical designs as well as designs incorporating the use of aluminum nitride ceramic capping. Previous testing completed on the Mark VII channel has shown aluminum nitride to resist electrochemical corrosion on the sidewalls and to reduce the incidence of interbar arcing.

Two areas on the forward sidewalls of the 1A1 channel have been modified for installation of prototypical 1A4 elements (Reference 7-1). Approximately 60 new sidewall elements were fabricated for installation at these locations. A map showing the relative location of the elements installed in the right and left forward sidewall sections are shown in Figures 7-2 and 7-3, respectively.

The right test section is comprised entirely of solid tungsten-copper (75% W, 25% Cu) elements and tungsten-copper based elements capped with tungsten. As noted in Figure 7-2, some of the tungsten caps were brazed on using a compliant braze, comprised of copper foil (0.004 and 0.010-inch thick) sandwiched on each side with a 0.002-inch thick gold-nickel braze foil (Handy & Harman P13). These compliant brazes were included to provide stress relief between the tungsten cap and the tungsten-copper base element.

The left wall sidebars included prototypical elements comprised of solid tungsten-copper, tungsten-copper based elements with tungsten caps, and copper based elements with tungsten caps. The aluminum nitride capped elements were located in Zone 2, as shown in Figure 7-3.

These test coupons are scheduled for testing at the CDIF in the first quarter of 1992.

Figure 7-2. Location of 1A4 Test Coupons in 1A1 Right Forward Sidewall

Figure 7-3. Location of 1A4 Test Coupons in 1A1 Left Forward Sidewall

7.2.3 Slag Rejector Activities

The installation of the TRW slag rejector was divided into 3 phases for installation at MSE over the last year and a half.

- Phase I: Included installing the TRW supplied denseveyor, piping and collection tank. The equipment is placed only for operation of the equipment as a replacement for the existing slag tank extension pipe.
- Phase II: This phase provides for the installation of controls necessary to operate the entire TRW-supplied slag rejection system on a continuous basis.
- Phase III: The final project phase will provide for installation and startup of the CDIF slag removal equipment and interfacing into the integrated slag rejector/slag removal system.

During the 15th quarter, Phase II of the slag rejector installation project was completed. This installation allows continuous slag rejection to the pit of Building 60 at the CDIF, and is presented schematically in Figure 7-4 (see 15th quarterly report for a description of the system).

The emphasis on testing during the 16th quarter was on checkout of the Phase II slag rejection system installation. Since there was no magnet, there was not sufficient voltage applied across the electrical isolators to simulate actual MHD operation for isolator breakdown during testing. The high-pot voltage supply was used to checkout the isolator design. High potential tests were performed up to 10 kV. The result of the May 1991 testing indicated that the slag rejection system is ready for further testing at a normal combustor voltage of 6 kV.

Figure 7-4. Slag Rejection System Schematic

7.2.4 Slag Grinder and Funnel Optimization Testing

The object of this testing was to make the slag tank funnel/grinder system (See Figure 7-5) as efficient in its task as possible. This includes maximizing the amount of small slag material bypassing the grinder and minimizing the amount of time that the large particles require to be broken up by the grinder.

Off-line testing was performed in the slag tank at the CDIF with modifications made to both the grinder and funnel. The details of this testing are presented in Appendix C. A plexiglas door was installed in place of the slag tank door and an underwater light was dropped down into the slag tank for observation. The slag tank was filled with water and the grind time was measured for several grinder (i.e., tooth ratio) configurations. Changes to the funnel configuration were also made. The best (most optimum) configuration will be installed and checked out when there is adequate slag production (i.e. CFC operation during the 17th quarter).

Initially, tooth ratios of 2:1, 3:1, 5:1, and 7:1 were proposed. Due to limited test time, only the 2:1 and 7:1 tooth ratios were tested. The 2:1 ratio used dull teeth while the 7:1 ratio used sharp teeth. The test with the 2:1 tooth ratio was performed using the existing funnel, and the 7:1 tooth ratio test was performed with the sloped funnel installed. All of these tests were performed by pouring in buckets of slag that had been saved from previous thermal tests. The basic results are as follows:

- The sloped funnel did not have any material hung up on it following the tests, whereas, the exiting flat funnel did.
- The grind time was basically the same for both tooth ratios.
- The 7:1 tooth ratio broke up larger chunks than the 2:1 ratio up to about "softball" size. Above this size, neither configuration was able to break the slag which bounced on top of the teeth.

Based on these results, the following recommendations have been made:

- 1) Retain the sloped funnel
- 2) Try out the 5:1 tooth ratio. Although the 7:1 ratio worked well and did not cause downstream plugging, the resulting slag may be too large when long duration runs are performed.
- 3) Hardface the cutter teeth which were worn after these tests. A tungsten-carbide material will be tried to enhance the wear properties.
- 4) Install a pressure tap into the gear and bearing boxes of the grinder to ensure equal pressure in the box and slag tank.

7.2.5 CDIF System Activities

7.2.5.1 Primary Cooling Water System (PCW)

To ensure that the PCW system meets the prototypical channel requirements for pH (7.0 ± 0.5), measurements of pH were made at the CDIF. The readings were not consistently at 7.0 after the demineralizer, and it is believed that the problem is due to chlorine blinding of the anion resins of the mixed bed system. The current plan is to install activated charcoal filters prior to the mixed bed demineralizer to remove the chlorine and continue to measure pH to ensure that it is in the 7.0 ± 0.5 range.

Dissolved oxygen measurements have also been made on the PCW water at the CDIF. The initial report indicates that the dissolved oxygen content in the PCW may be out of range (above 3.0 ppm). More measurements will be taken during the 17th quarter to confirm this fact. If this is true, then the atmospheric vented tanks in the system will be blanketed with nitrogen.

7.2.5.2 Iron Oxide System

No new work was accomplished on this system during this reporting period. Two new progressive cavity slurry pumps will be delivered and installed during the 17th quarter.

Figure 7-5. Slag Tank Flat Funnel Configuration

7.2.5.3 Coal System - Coal Size Distribution Variation

Testing during this reporting period saw dramatic swings in the flowability and reading of coal. Based on the coal size distribution analyses taken during MHD testing at the CDIF, it is possible that there are dramatic swings in combinations of the following:

- Coal
- Coal processing operations
- Coal processing equipment adjustment
- Coal sampling methods

Within the last year, the "nominal" operation of the CDIF coal system has yielded processed coal anywhere between 35% minus 200 mesh to more than 90% minus 200 mesh. These results are based on wet sieve particle size distribution analysis.

Specifically during the testing in May 1991, it appears as though there were major fluctuations in the processed coal used for testing. For every test during the May 1991 testing, samples taken by MSE in the on-line dense phase coal sampling location were sent to the CT&E (Commercial Testing and Engineering) laboratory for "wet" particle size determination using standard mesh sieves. As a check on this methodology, four duplicate samples were sent to Babcock and Wilcox Alliance Research Division and analyzed using a Microtrac particle size analyzer for the range of 0.2 to 300 microns.

The results of wet sieve analysis appear as Table 7-3. A graph of cumulative percent minus 200 mesh is presented as Figure 7-6 for the entire test series. A comparison of the wet sieve results and Microtrac results appears in Table 7-4. The initial results are as follows:

Figure 7-6. CT&E Wet Sieve Analysis - Minus 200 Mesh Comparison CDIF May 1991 Testing

TABLE 7-3. CT&T WET SIEVE ANALYSIS - CDIF PULVERIZED COAL MAY 1991

Test	Coal Batch	Lab	Analysis Report No.	Plus	-50	-60	-80	-100	-120	-140	-170	-200	-270	-325	-400	-500	Total
91-SREJ-01	#2033	CTE	71-12510	0.8	99.2			91.8		80.5		60.4	34.4	31.2		10.6	100.0
91-SREJ-02	#2130	CTE	71-12511	0.6	99.4			94.1		84.4		65.4	46.7	37.1		22.1	100.0
	#2320	CTE	71-12512	0.7	99.3			93.2		85.0		72.0	58.5	50.3		26.1	100.0
91-SEED-02	#232	CTE	71-12935	1.8	98.2			85.7		71.1		56.6	44.3	38.7		27.4	100.0
	#1132	CTE	71-12934	1.1	98.9			88.6		73.0		56.0	40.2	33.0		18.0	100.0
91-SEED-03	#1833	CTE	71-12900	0.5	99.5			92.7		80.7		63.5	45.5	36.9		18.2	100.0
	#2235	CTE	71-12901	0.7	99.3			92.0		79.7		59.1	30.2	26.1		9.9	100.0
91-SREJ-03	#1015	CTE	71-13486	0.4	99.6			93.9		82.7		64.7	41.0	32.5	15.2	7.8	100.0
	#1330	CTE	71-13487	1.3	98.7			86.7		72.8		53.4	35.6	28.3	11.4	5.7	100.0
91-SREJ-04	#1100	CTE	71-13488	1.5	98.5			81.6		59.1		35.2	17.6	11.9	5.5	3.1	100.0
	#1315	CTE	71-13489	1.4	98.6			81.5		54.8		36.5	17.2	13.9	9.6	4.5	100.0
91-COAL-01	#1120	CTE	71-13490	0.7	99.3			89.9		75.9		53.0	24.3	22.4	11.6	5.9	100.0
	#1200	CTE	71-13491	1.0	99.0			86.3		69.4		49.0	21.4	19.8	15.1	7.8	100.0
	#1252	CTE	71-13492	2.3	97.8			75.2		56.7		38.2	17.4	15.1	7.3	4.3	100.0

**TABLE 7-4. COAL SIZE DISTRIBUTION COMPARISON, CT&E, VS. B&W
(CUMULATIVE % PASSING)**

		Normal 91-SREJ-02 05-01-91 21:30		Normal 91-SREJ-04 05-16-91 11:00		Fine 91-COAL-01 05-17-91 11:20		Normal 91-COAL-01 05-17-91 12:52	
Mesh	Microns	CT&E	BW	CT&E	BW	CT&E	BW	CT&E	BW
50	300	99.4	99.4	98.5	99.3	99.3	99.5	97.8	98.9
100	150	94.1	94.6	81.6	77.5	89.9	90.4	75.2	75.9
140	106	84.4	81.5	59.1	62.3	75.9	79.0	56.7	61.5
200	75	65.4	66.4	35.2	44.6	53.0	67.1	38.2	48.9
270	53	46.7	48.7	17.6	31.3	24.3	53.9	17.4	34.1
325	44	37.1		11.9		22.4		15.1	
400	37		35.1	5.5	21.1	11.6	44.9	7.3	26.6
500	26	22.1	24.8	3.1	14.5	5.9	37.3	4.3	17.8
	18		15.7		9.1		27.6		12.7

- 1) The coal at the start of testing (91-SREJ-01 and 91-SREJ-02), that was stored in the system since February, is substantially more fine than coal taken from the pad later on in testing (91-SREJ-04, 91-COAL-01). The extreme variation is between 72% minus 200 mesh for 91-SREJ-02 and 35% minus 200 mesh for 91-SREJ-04.
- 2) The Microtrac analysis for 91-COAL-01 indicates that the baghouse fines could have been mixed into the normal coal at a mix of 20 to 40% baghouse fines to 60 to 80% normal coal (67% minus 200 mesh at 11:20 vs. 49% minus 200 mesh at 12:52). The sample taken at 11:20 was mixed fine coal, whereas the sample taken at 12:52 was normal coal comparable to 91-SREJ-04.
- 3) The Microtrac analysis for "fine" coal at 11:20 of the fine coal test (91-COAL-01) is not substantially different from coal sampled during 91-SREJ-02 for sizes 200 mesh and larger. However, there are definitely more fines below the 400 mesh size range during the fine coal test, as expected.

The variables that need to be understood are:

- 1) Coal - Did the raw coal properties change substantially during this test series?
- 2) Coal Operations - Were there changes in coal system operation or equipment modifications that could account for the differences in size distribution?
- 3) Coal Sampling - Were the coal samples taken uniformly during the test series using the same technique and equipment?

A possible reason for the swings in coal size and moisture content could be the locations that the coal came from or was stored. Table 7-5 presents the best guess at where the coal that was processed for testing came from, and when it was introduced into the system.

TABLE 7-5. BEST GUESS MAY 1991 TESTING, CDIF COAL SITUATION
(Amounts in Tons of Processed Coal)

Date	Coal Process Number	Coal Supply	CFC Test	Amount Processed (+)	Amount Burned (-)	Net Amount Left (=)	Coal Changes Noted
FEB 1991	91-10	In-System				25	
04/23	91-11	In-System		10		35	
04/29			91-SREJ-1		11	24	
04/30	91-12	In-System		32		56	
05/01			91-SREJ-2		41	15	
05/02	91-13	In-System Plus Pad		30		45	ERRATIC
05/03			91-SEED-1		9	36	
05/07	91-14	PAD	91-SEED-2	54	34	56	
05/09			91-SEED-3		32	24	
05/13	91-15	PAD		20		44	
05/14			91-CALB-1		1	43	
05/15			91-SREJ-03		43	0	
05/16	91-16		91-SREJ-04	57	34	23	MORE COARSE
05/17			91-COAL-01		19	4	

7.2.5.4 Coal System - Coal Mass Flow Meter Calibration

On May 14, 1991, a test was run at the CDIF (91-CALB-1) to calibrate the two Endress + Hauser (E+H) meters that are used to measure and control coal flow to the precombustor and the main stage of the combustor.

The coal injection system flow and instrumentation schematic is shown in Figure 7-7. Under normal operation, coal is split at the outlet of the primary injector vessel into two streams which feed the precombustor and the main stage of the combustor. The coal flow rate for each stream is measured by individual E+H meters. The sum of these two individual measurements are continuously compared with the total coal rate derived from the primary injector vessel load cell and corrected accordingly. Hence, it is assumed that the two E+H meters always have the same relative measurement error. If, on the other hand, the two E+H do not have the same relative measurement error, then the actual coal split between the precombustor and the main stage would be different than what is measured, even if the total coal flow is correct.

The objective of 91-CALB-1 was to reconfigure the coal feed system in such a way that the relative measurement errors of the two E+H meters could be compared and characterized. This would check the validity of the above assumption and allow appropriate corrections to be made.

Test Configuration and Conditions

Figure 7-8 shows the coal feed system schematic for the E+H calibration test. The main configuration change is that the coal stream that is normally sent to the main stage was diverted to the Blue Vessel. The main stage E+H meter was relocated from Building 60 to the Blue Vessel building. The combustor

Figure 7-7. CDIF Coal Injection System Flow and Instrumentation Schematic to CFC

pressure was approximately 40 psia (CFPC only), while the Blue Vessel back pressure was set at 85 psia. The latter condition was necessary in order to get a reading from the main stage E+H meter, which has been turned to read over a relatively small pressure range (approximately 70 to 90 psia).

Test Results

The 10 minute average of load cell and flow rate data from 1 second data is as follows:

Bldg. 20 load cell = 210.6 lb/min

Blue Vessel load cell = 181.3 lb/min

CFPC E+H reading = 34.7 lb/min

CFC E+H reading = 268.9 lb/min

A simplified schematic is shown in Figure 7-9. The difference between the two load cell measurements is 29.3 lb/min, which is the "actual" coal flow to the CFPC if it is assumed that the load cell measurements are absolutely correct and that no coal escapes within the system, i.e. through the Blue Vessel vent.

Initial Interpretation of Data/Corrective Action

From the above data, the relative error of the two E+H meters was determined as follows:

- The CFC E+H reading was high by $268.9/181.3 = 1.483 = 48.3\%$
- The CFPC E+H reading was high by $34.7/29.3 = 1.184 = 18.4\%$

Figure 7-9. Simplified Schematic of E+H Calibration Test

From the above calculations, it is shown that the relative error of the CFC E+H meter was found to be higher than the CFPC E+H meter. In order to make the relative error of the two meters the same, the multiplication constant of the CFPC E+H reading was corrected by $1.483/1.184 = 1.253$. This change was performed after 91-CALB-1 and was in place during 91-SREJ-3, 91-SREJ-4, and 91-COAL-1.

Since only the sum of the two E+H meters is corrected back to the load cell reading, the net effect of the above change was to alter the coal split between the precombustor and the main stage. The ratio of the old to new CFPC coal flow rate is thus $1/1.253 = 0.80$. The precombustor is thus receiving only 80% of the coal it received prior to the change. The effect on the main stage coal is much less (3% increase), since the main coal flow rate is over 6 times larger than the precombustor coal flow rate.

Concerns Regarding E+H Calibration Test

- 1) The calibration test setup, in which the majority of the coal flows to the Blue Vessel and the "actual" precombustor coal flow is determined by the difference of two relatively large numbers, allows for load cell errors to be magnified by a factor of 6 or more. In other words, a load cell error of 3% would result in an overall PC calibration error of about 20%.

The following example should illustrate this point:

Assume that the Blue Vessel load cell measurement is high by 3%, which is probably on the high side but still a possibility. Thus, the load cell reading would be 186.7 lb/min instead of 181.3 lb/min. The "actual" CFPC coal flow would be $(210.6 - 186.7) = 23.9$, instead of 29.3 lb/min.

The relative E+H meter errors would be as follows:

- The CFC E+H reading was high by $268.9/186.7 = 1.440 = 44.0\%$
- The CFPC E+H reading was high by $34.7/23.9 = 1.452 = 45.2\%$

In this case, the two relative errors would be the same and thus no correction to the flow split would have been made. On the other hand, if the Blue Vessel load cell reading was 3% on the low side, a correction factor of 1.52 would have been applied to the CFPC E+H reading. Thus, within the measurement accuracy of the load cells, the correction to the CFPC E+H meter could have just as easily been 1.0 or 1.5 instead of 1.25.

- 2) Another unknown which can significantly affect the accuracy of the calibration is the amount of coal lost through the Blue Vessel vent line. If 3% of the main stage coal is actually vented, this is equivalent to the load cell being off by 3% as discussed in the above example.
- 3) Given the significant differences between the two E+H meters (i.e. size, absolute velocity, allowable pressure range), is it valid to assume that the difference in relative error will always be the same? The CFPC E+H meter is required to operate over a much larger pressure range (30 to 90 psia) compared to the CFC E+H, and thus would be expected to have a lower accuracy.
- 4) The accuracy of the CFPC E+H meter is also likely to be a function of operating pressure due to the fact that it must operate over a large range of velocities, gas densities, and gas/solid volume ratios. Under nominal 50 MW_t conditions, both meters operate at approximately 85 to 90 psia. The calibration, however, was performed with the CFPC E+H meter at 45 psia and errors of each meter operating at 85 psia would likely yield different results than if one meter is at 45 psia and the other is at 85 psia.
- 5) Is 10 minutes of data enough to characterize the linearity and drift of these instruments?

Recommendations

- 1) The corrections made to the CFPC meter as a result of the E+H calibration tests are called into question based on the concerns listed above. The newly determined correction factor should be verified with additional calibration tests prior to acceptance.

- 2) The calibration of the coal split should be retained as a high test priority. The accurate metering of coal flow to the precombustor is absolutely critical to the understanding of overall CFPC performance as well as to help diagnose CFPC operational problems such as fouling.
- 3) The accuracy of the calibration can be significantly improved by flowing the smaller stream (CFPC coal) to an independent vessel with load cell instrumentation. The larger stream (main stage coal) should be sent to the Blue Vessel. This would allow for three independent load cell readings to determine the three coal flow rates (main stage, precombustor, and total). The accuracy of the CFPC coal flow measurement would be improved by a factor of 6 to 7. This approach would also allow the back pressure of each line to be individually controlled.
- 4) The length of the calibration test(s) should be as long as possible within the storage capacity of the facility (believed to be 20 minutes) in order to obtain information on instrument drift during operation.
- 5) The calibration test should be repeated for several different coals and conditions within the range of expected usage as follows:
 - 96 psia back pressure
 - 86 psia back pressure
 - 76 psia back pressure
 - 12% moisture coal
 - 5% moisture coal
 - Solids to gas mass ratio of 10:1
 - Solids to gas mass ratio of 5:1

Further Testing

A recalibration of the Endress + Hauser meters will be performed during the 17th quarter. This will involve running all of the coal from the primary injector vessel to the Blue Vessel and trying to obtain good mass closure (including coal captured by filter receiver located on Blue Vessel vent line).

Both of the above concerns can be addressed through the following tests:

- 1) Configuration 1: Coal feed system configured to run coal from primary injector vessel to Blue Vessel at nominal CFC coal rate (210 lb/min). CFC E+H meter installed in line.

Condition	Coal Flow Rate	Blue Vessel Back Pressure	Duration
1	210 lb/min	85 psia	20 min

- 2) Configuration 2: Coal feed system configured to run coal from primary injector vessel to Blue Vessel at nominal CFPC coal rate (30 lb/min). CFPC E+H meter installed in line.

Condition	Coal Flow Rate	Blue Vessel Back Pressure	Duration
2	30 lb/min	85 psia	20 min
3	30 lb/min	45 psia	20 min
4	30 lb/min	65 psia	20 min
5	30 lb/min	85 psia	20 min

Notes:

- 1) After each condition, the contents of vent line filter receiver should be weighed in order to perform a mass balance on the system.
- 2) Configuration 1 was proposed in order to perform a mass balance at the same mass flow as that expected for the calibration test, since the error between the load cell readings is likely to be a function of mass flow rate.
- 3) Configuration 2 will allow determination of how the relative error of the E+H meter varies as a function of back pressure. Once this is known, the calibration test could be performed at a back pressure of 45 psia and the error corrected back to 85 psia.
- 4) All conditions should be run with the same batch of coal (with the same processing history) in order to minimize coal moisture variations from condition to condition.
- 5) If consistent readings are not obtained between conditions 2 and 5 above, then conditions 3 to 5 should be repeated.

7.2.5.5 Seed System

No new work was accomplished on this system at the CDIF during the reporting period.

7.2.5.6 Magnet

All MHD testing during the quarter was done without the magnet. The water leak that developed in the magnet coil during the 15th quarter has not as yet been repaired. Several consultants have been hired by DOE to determine the best fix methodology. The repair will be made during the 17th quarter.

7.2.5.7 Oxygen System Upgrade

The oxygen storage and vaporization system at the CDIF was expanded to store 43 hours of oxygen for testing. This system will be checked out for operation during the 17th quarter.

7.2.5.8 Westinghouse Current Consolidation Cabinet Installation

Design work was completed during this reporting period. The Westinghouse current consolidators will be installed in a new building during the 17th quarter. Checkout will be initiated prior to testing the unit under MHD power.

7.3 TEST PLANS

The test plans for future quarters is shown in Figure 7-10, "ITC CDIF Test Schedule". Specifically for next quarter, the CDIF testing will emphasize attainment of:

- Power takeoff (PTO) testing which includes the Westinghouse current consolidators and Avco/TDS floating electrode confirmation
- Slag rejector/removal checkout
- ITC system checkout (50-hour continuous electrical test)

Test time will be limited next quarter due to the continued downtime required for the following facility modifications:

- 1) DAS (data acquisition system) installation
- 2) 50-hour oxygen system upgrade
- 3) Slag removal system installation (Phase III)
- 4) Anode current consolidation installation
- 5) Rectangular second stage installation
- 6) Magnet repair
- 7) High voltage room configuration

FIGURE 7-10. ITC CDIF TEST SCHEDULE AS OF 08/15/91

ITC TEST GROUPS - CONFIRMATION TESTING IS NUMBERED

FY-1992

FY-1993

- (1) Checkout Facility Modifications
- (2) Slag Removal System Operation
- (3) Anode CC Testing
- (4) PTO Testing
- (5) 50-Hour Cont. Elec.
- (6) Seed Utilization/Efficiency
- (7) Finer Coal Test Confirmation

- DVT --POC Design Verification Testing
- (A) Checkout Testing Combustion Subsystem
- (B) 1A4 50-Hour Cont. Elec. Tests

DVT Channel Plus Duration Testing

CDIF FACILITY ACTIVITIES

- 1 = C.S.R./S.R.S PHASE 3
- 2 = PIPING TIE-IN 50 HOUR O₂, N₂
- 3 = RECT. S.S. INSTALL
- 4 = DAS INSTALLATION
- 5 = INSTALL CURRENT CONSOLE ANODE CABINET
- 6 = INSTALL LPCS
- 7 = INSTALL POC COMBUSTOR
- 8 = CURRENT CONSOLE COMPLETION
- 9 = INSTALL 1A4
- 10 = DETAILED 1A4 INSPECTION
- 11 = DETAILED COMBUSTOR INSPECTION

Toward the end of the 17th quarter, testing at the CDIF will resume to checkout the modifications made to the facility and test hardware. In addition, a 50-hour continuous electrical test will be attempted.

The testing required during the 17th and 18th quarters at the CDIF is shown in Table 7-6.

REFERENCE FOR SECTION 7

- 7-1. TRW, MHD Integrated Topping Cycle, Fifteenth Quarterly Technical Progress Report, February 1991 through April 1991, MHD-ITC-91-435, U.S. Department of Energy Contract No. DE-AC22-87PC90274, Section 5.

TABLE 7-6. ITC TESTING PRIORITY LIST FOR FALL 1991 AT THE CDIF

Priority	Test Series Description	Estimated Number of Tests and Duration	Configuration	Test Window
1	Facility Readiness Power Train Testing a) OFV/CFPC only b) CFC/Conductivity c) Channel/Electrical	2 at 2 hours 2 at 4 hours 2 at 4 hours	Coal configured to Blue Vessel if Required Complete Test Train Complete Test Train - KC Resistive Fall Back	2 Weeks
2	Power Management Testing Testing Group 1 Baseline Characterization of Westinghouse Fwd PTO, TDS Aft PTO and initial characterization of bleed resistor network Testing Group 3 Contingency operating modes of Westinghouse Fwd PTO.	3-4 at 4-8 hours	Complete Test Train Except Slag Rejector/Removal System not operated during this test series	1 Week
3	Slag Rej/Removal & Rect. 2nd Stage Testing Continuous Slag Rejector and Removal checkout under power (including checkout of any modifications to grinder and/or ventline system). Characterization of rectangular second stage performance including conductivity and power data (load lines) at both Ref 1 and Ref 2 operating conditions and $\phi 2$ variations.	3 at 8-16 hours	Complete Test Train	2 Weeks
4	Power Management Testing Testing Group 2 Proportional control of Westinghouse Fwd PTO; fine tuning of bleed resistor network.	2-3 at 4-8 hours. These tests can be performed immediately following priority 2 in this list if it is the most effective utilization of support personnel	Complete Test Train	1 Week
5	50-Hour Continuous Electrical Test 50-hr continuous electrical test including continuous iron oxide injection.	Estimate minimum of 3 tests varying in duration from 12 to 50 hours 1 at ~4 hours	Complete Test Train	3 Weeks
6	Fine Coal Testing Repeat "fine" coal tests (determine if excessive precombustor fouling observed during May was due to coal grind)		Complete Test Train	1 Week
7	Seed Utilization Testing Continuation of seed utilization efficiency and/or slag recovery tests	at ~4-8 hours	Complete Test Train	2 Weeks

8. MODELING AND PERFORMANCE ANALYSIS ACTIVITIES (SUBTASK 1.3)

Subtask 1.3 of the ITC program, Power Train Performance Analysis, encompasses a broad range of activities aimed at: 1) understanding the fundamental chemical, electrical, and flow phenomena which occur in an MHD topping cycle power train, and 2) analyzing and interpreting the results of the many ongoing test programs to determine hardware performance. By thoroughly understanding the basic processes and knowing how the components and subsystems perform, information is obtained on ways to design better equipment and assess the risks of scaling up to the next level of development.

Modeling and performance analysis are ongoing parts of the ITC program. Two major efforts which are part of this subtask and which will continue throughout the contract are cold flow modeling of the combustion subsystem components and analysis of power train performance data obtained during testing at the CDIF. From time to time, other modeling and analysis activities arise from or are performed to support these major modeling and performance analysis efforts.

During the last quarter, combustor performance analysis activities focused on four areas: combustor slag recovery, slag tank operation, precombustor slagging behavior, and sidewall voltage behavior. Over the last several months, the slag recovery model has been re-evaluated and refined. Results will be presented in a separate topical report on combustor slag recovery scheduled for release in September, 1991. One aspect of slag recovery modeling is discussed in Section 8.1 of this quarterly report, namely the slag tapping efficiency.

In Section 8.2, an analysis of slag tank operation during the recent slag rejector checkout tests is presented. These tests have underscored the importance of maintaining an open, free-flowing gas vent in the slag tank during long duration operation. Modifications to the vent line have been made based on the results of these tests, which will be evaluated during the upcoming test series.

In Section 8.3, an analysis of precombustor slagging behavior is presented. The analysis was performed to identify the cause of the increased slagging observed during the most recent coal fines test, 91-COAL-1.

In Section 8.4, sidewall voltage behavior is described. The sensitivity of sidewall behavior to different influences including left- and right-sidewall voltage profiles, iron oxide injection, generator loading, and ballast resistors was investigated.

8.1 SLAG TAPPING EFFICIENCY

8.1.1 Introduction

One of the important parameters which helps determine the overall combustor slag recovery is the so-called slag tapping efficiency. In the MHD combustor, slag is removed from the combustor as a molten fluid through a circular slag tap located at the downstream end of the slagging stage. The slag tapping efficiency is defined as the percentage of molten slag flowing along the combustor walls upstream of the slag tap that is subsequently captured in the slag tank. Thus, if 90% of the original coal ash is centrifuged to the wall and absorbed into the liquid slag upstream of the slag tap, and the tapping efficiency is 80%, the overall slag recovery would be 72%. The remaining 20% of the slag flowing along the wall would miss the tap and spill over the baffle. Note that the value of slag tapping efficiency is always higher than the overall slag recovery, since a portion of the original coal ash remains airborne and thus escapes from the slagging stage with the gas.

At the conditions present in the MHD combustor, the flow of slag is influenced primarily by gas shear stresses, with gravity forces exerting only a secondary influence. Hence, it is usually valid in most regions of the combustor to assume that the slag will flow along the direction of gas streamlines. This has been repeatedly verified during post-test observations of the internal surfaces of the combustor. Thus, in the absence of a slag baffle, the slag tapping efficiency would be:

$$\eta_{\text{tap}} = \frac{d_{\text{tap}} = (1 + S_w^2)^{1/2}}{\pi D_c} \times 100 \quad (1)$$

where: η_{tap} = slag tapping efficiency

d_{tap} = diameter of slag tap

D_c = combustor diameter

S_w = wall swirl number, or the ratio of tangential to axial velocity at wall

The flow angle for this case is defined as:

$$\phi = \tan^{-1}(1/S_w) \quad (2)$$

Thus for $d_{\text{tap}} = 12$ inches, $D_c = 30$ inches, and $S_w = 3$, η_{tap} would be 40.3%, with a slag flow angle of approximately 18 degrees measured from the azimuthal direction. This is graphically shown in Figure 8-1, where slag streamlines have been drawn ignoring the influence of the baffle. Note that to achieve 100% slag tapping efficiency without the aid of a slag baffle or other slag tap enhancement, the tap would need to be approximately 30 inches in diameter, which would be equal to the combustor diameter. A slag tap of this size would not be practical in an MHD combustor due to large radiative heat losses to the slag tank.

The slag baffle shown in Figure 8-1 is designed to enhance the slag tapping efficiency over the above minimum, or freestream value. As the gas flow approaches the baffle, the gas streamlines at the wall run parallel with the baffle, allowing more of the slag to be directed towards the slag tap. This, in effect, increases the wall swirl number, S_w , since the axial velocity decreases to zero at the baffle. According to equation (1), an increase in S_w leads to a corresponding increase in the tapping efficiency.

Figure 8-1. Slag Flow Streamlines (Ignoring the Effect of the Baffle)

An ideal slag tap/baffle configuration would be one in which the slag tap is positioned flush against the baffle and extends far enough upstream to ensure that any slag that misses the tap on the upstream end is directed completely around the combustor circumference and into the tap at the bottom of the combustor. However, due to mechanical design considerations, the present workhorse slag tap does not extend all the way to the slag baffle. Instead, there exists a 3-inch gap which allows a portion of the slag flowing adjacent to the baffle to bypass the tap.

For this situation, the calculation of slag tapping efficiency is more difficult. Two approximate calculation methods have been developed, however, to effectively bracket the problem. The first method assumes that the only effect of the slag baffle is to alter the gas streamlines and thus the slag streamlines. Thus by integrating the wall swirl number across the length of the tap, one can determine an effective swirl number which can be used in equation (1) to determine the slag tapping efficiency. Note that this method is conservative since it implies that the remainder of slag will flow through the gap between the baffle and the slag tap, resulting in a liquid slag layer that is up to 3 times as thick as adjacent regions upstream. In the actual case, the liquid slag will tend to even itself out in this region, thus allowing more slag to intercept the tap.

An alternate calculation approach is to assume that in the vicinity of the baffle, the slag flow is purely in the tangential direction, with a constant mass flow per unit width. In this case, the slag tapping efficiency would be simply:

$$\eta_{\text{tap}} = d_{\text{tap}} / (d_{\text{tap}} + z) \quad (3)$$

where z is the distance between the baffle and the slag tap. This would give the upper limit of slag tapping efficiency, except for the case in which no slag can spill over the baffle, in which case the slag tapping efficiency is 100%.

In the following section, the slag tapping efficiency is calculated for several different slag tap sizes using each of the two methods, after which the results are discussed and compared.

8.1.2 Slag Tapping Efficiency Calculations

As mentioned above, the first calculation method involves determining the effective wall swirl number in the vicinity of the slag tap. In order to determine the dependence between wall swirl number and the distance from the baffle, flow visualization tests were conducted utilizing a 1/3 scale transparent cold flow model of the 50 MW_t MHD combustor. Tangential and axial injection flow were set to preserve the swirl number in the actual combustor. Figure 8-2 indicates the direction of gas flow at the wall as a function of distance from the baffle as determined from air model flow visualization. The tightening of the swirl, as indicated by a decrease in flow angle is clearly seen in the figure. In Figure 8-3, the wall swirl number based on the measured flow angles is plotted as a function of distance away from the baffle. The swirl number is normalized to its freestream value while the distance to the baffle wall is normalized to the combustor diameter D_c . The relationship shown in Figure 8-3 is well approximated by the following equation:

$$\frac{S_w}{S_{w,\infty}} = 1.0 + \frac{0.06}{(z/D_c)^{1.4}} \quad (4)$$

where: S_w = ratio of tangential to axial velocity at the wall far upstream of baffle region
 z = distance from baffle

For the 50 MW_t MHD combustor with a 12-inch tap located 3 inches upstream of the baffle ($z/D_c=0.1$), integration of equation (2) over the length of the slag tap yields a normalized swirl number of 1.45, which corresponds to a slag tapping efficiency of 57% according to equation (1), for a freestream wall swirl number of 3. Table 8-1 lists the results of the calculations.

Figure 8-2. Flow Angles at the Combustor Wall Just Prior to the Slag Tap as Determined by Flow Tufts in the Cold Flow Model

Figure 8-3. Swirl Number at the Wall as a Function of Distance from the Baffle as Determined from Air Model Measurements

TABLE 8-1. COMPARISON OF SLAG TAPPING EFFICIENCY CALCULATIONS

Tap Diameter d_{tap}	Distance From Baffle, z	$\frac{S_w}{S_{w,\infty}}$	Method 1 η_{tap}	Method 2 η_{tap}
9"	4.5"	1.38	41%	67%
12"*	3"	1.45	57%	80%
14.5"***	2"	1.52	72%	88%

*Current workhorse combustor dimensions

**Prototypical combustor dimensions

The prototypical combustor was designed with a larger slag tap opening of 14.5 inches in an effort to improve the slag tapping efficiency of the combustor. In addition, the gap between the slag tap and the baffle was decreased to 2 inches. In this case, the wall swirl number is integrated from $z/D_c = 0.067$ to 0.55, and a normalized swirl number of 1.52 is obtained. This yields a calculated slag tapping efficiency of 72%, again for a freestream swirl number of 3.

The slag tapping efficiency values calculated using method 2 are also shown in Table 8-1. For the workhorse combustor with a slag tap diameter of 12 inches and a gap of 3 inches, the calculated slag tapping efficiency is 80%. For the prototypical tap of 14.5 inches, the calculated slag tapping efficiency is 88%. The actual slag tapping efficiency falls somewhere between the two calculations presented here.

8.1.3 Cold Flow Model Investigation of Slag Tap Enhancements

In addition to measuring the change in gas streamlines as the flow approaches the baffle, the cold flow model was also utilized to evaluate potential slag tap enhancements that could be tested on the hot-fired combustor at the CDIF.

The first modification was to insert a guide between the baffle and the slag tap as shown in Figure 8-4. This was intended to direct or guide slag flow between the baffle and tap into the slag tank. Three variations were tested as shown in Figure 8-4. Water was used as the working fluid and was injected along the streamline which would flow between the baffle and tap. The height of the guide required to prevent spill over was approximately 1 inch (3 inches in 50 MW_t workhorse combustor) for all three cases tested. With sufficient height to prevent spill over, guide configurations A and B had problems with flow or leakage around the outer end of the guide and also underneath the guide due to the high shear forces. Thus, guide configurations A and B needed to be extended more towards the center of the tap and also downward into the tap as shown in Figure 8-4 (guide sections 1 and 2 of side view). After these modifications were made, the slag tapping efficiency improved.

Guide configuration C shown in Figure 8-4 seemed to operate the most efficiently of the three cases, and did not need a downward extension piece since it was positioned flush with the back of the slag tap. Furthermore, the guide in this position was observed to create a strong swirl in the slag tank water indicating that the flow was being redirected into the slag tank. Guide C also has the advantage over configurations A and B in that the guide does not hang directly over the tap, which may eventually cause plugging problems. The best dimensions for guide configuration C, along with the corresponding workhorse dimensions, are shown in Figure 8-5.

The second modification tested in the cold flow model was a re-entrant baffle as shown in Figure 8-6. The intended purpose of the re-entrant baffle is to prevent liquid slag leakage through the baffle bore, and to redirect or centrifuge the slag back toward the combustor walls. This would give the slag a second chance to intercept the slag tap. Two configurations were tried as shown in Figure 8-6. Configuration A is just a straight cylinder attached to the baffle bore, and configuration B is a cylinder with a small lip at the end.

Figure 8-4. Guide Configurations Tested in the Cold Flow Model for Improving Slag Tapping Efficiency

Water was again utilized for slag flow visualization. Although the amount of water that spilled over the baffle was reduced relative to the baseline configuration, the spillover was still much greater than that achieved with the slag tap guides described in the previous paragraphs. Hence, it was concluded that slag tap guide configuration C appears to be the most promising slag tap enhancement, short of moving the tap so that it is flush with the baffle.

8.1.4 Summary and Conclusions

- 1) In the absence of a slag baffle, slag tapping efficiency for the 50 MW_t MHD workhorse combustor would be approximately 40%.

Figure 8-5. Best Guide Configuration

Figure 8-6. Re-entrant Configurations Tested in the Cold Flow Model for Improving Slag Tapping Efficiency

- 2) Two calculation methods are presented for the case of a slag tap located just upstream of a slag baffle which effectively bracket the actual slag tapping efficiency. Slag tapping efficiency for the workhorse combustor with a 12-inch slag tap is estimated to be between 57 and 80%, and between 72 and 88% for the prototypical combustor with a slag tap of 14.5 inches.
- 3) Several different slag tap enhancements were evaluated in the cold flow model in order to select one or two of the most promising configurations for future hot-fired testing. A slag guide originating at the baffle and running tangent with the slag tap (guide configuration C) was determined to be the most promising configuration. All of the slag guides tested appeared to be more effective than installing a re-entrant baffle.

8.2 ANALYSIS OF SLAG TANK OPERATION

8.2.1 Introduction/Background

In order to operate continuously for long durations (over 10 hours), the 50 MW_t MHD coal-fired combustor (CFC) must be integrated with a continuous slag rejection system. Over the past year, such a system has been installed and integrated at the CDIF and has been checked out in a step-wise fashion. Checkout tests of the complete slag rejection system were recently completed in May, 1991.

A layout of the system is shown in Figure 8-7. The slag rejection system consists of a slag tank, denseveyor, and collection tank, along with associated piping, valves, instrumentation, and controls. The function of the slag tank is to quench the incoming molten slag from the combustor and grind the slag so that no particles are greater than approximately 2 inches. After leaving the slag tank, the slag drops down to the denseveyor, where depressurization of the slag/water mixture is performed every 30 minutes. Once at atmospheric pressure, the mixture is transferred to a collection tank, which is brought down to ground voltage every 90 minutes. From this point, the slag and water mixture is transferred to the slag removal system, where the slag is dewatered, weighed, and pneumatically transferred to a temporary storage area.

A more detailed schematic of the slag tank is shown in Figure 8-8. The operation of the slag tank is described in detail in Reference 8-1. Cold water (approximately 60°F) is added to the slag tank via a pipe located 3 to 4 inches below the nominal water level. The tank is instrumented with thermocouples located along the tank walls to detect water level. Currently, water level is adjusted by increasing or decreasing the fill rate. A combination gas/water vent is located on the opposite side of the tank. A vent cap is situated on the end of the vent line which allows water to enter through the bottom and gas through the top. Additional cold water is added to the vent line outside the slag tank to cool its contents prior to entering an electrical isolation hose. A mechanical grinder is located near the bottom of the tank which grinds the slag prior to leaving the bottom of the tank. A slag funnel is located just above the slag grinder to guide the large slag pieces into the grinder.

The slag tank operational requirements are as follows:

- 1) Maintain water temperature sufficiently below saturation temperature (approximately 200°F) in order to minimize the flashing of steam on shutdown.
- 2) Vent slag tank gases to quench duct. This ensures that gas pressure in the slag tank is slightly lower than combustor pressure, thus preventing any steam generated by the slag quenching process from entering the combustor.
- 3) Maintain water level within specified limits. If water level drops too low, then uncooled portions of the slag tank will be in contact with hot slag tank gases. If water level is too high, then gas vent will be underwater and gas flow will be restricted.
- 4) Maintain vent water temperature below 190°F to protect electrical isolation hose.

Reference 8-1 describes some of the slag tank operational problems that have been experienced during recent CDIF testing. The most significant problem is the tendency of the vent line to become partially plugged with slag and char. As the vent line begins the plug, its flow capacity is reduced, which in turn

Figure 8-7. CDIF Slag Rejector Assembly

Figure 8-8. Schematic of Slag Tank - Baseline Configuration

means that the slag tank fill rate must be reduced in order to maintain a constant water level. Sometimes the fill rate must be set as low as 2 gpm. In general, reducing the slag tank fill rate tends to lead to an increase in slag tank water temperature above 200°F, as less water is used to carry away the same heat input from the slag and tank gases. In order to avoid this operational scenario, the slag tank vent line must be thoroughly purged and cleaned every 3 to 5 test starts.

Another problem associated with continuous slag tank operation is slag accumulation in the funnel located just above the slag grinder. Prior to the April-May 1991 test series, a total of nine tests had been conducted with the slag funnel installed, with the longest test 200 minutes in duration. During approximately half of those tests, funnel slag accumulation was observed, including one test in which the grinder was not installed. Although in most cases the accumulated matter was a small fraction of the total slag rejected, it was concluded that additional tests were needed to verify that the funnel/grinder would not plug over longer test durations.

During the April-May 1991 test series, a number of tests were conducted to check out the fully operational slag rejector system. During these tests, several configurational and operational changes were made to the slag tank to help understand and ultimately improve its operation and control. The purpose of this section is to analyze the results of these tests and to provide recommendations for future slag tank testing at the CDIF.

8.2.2 Summary of Test Results

Table 8-2 lists the CDIF tests conducted during the April-May 1991 test series. The first two tests (91-SREJ-1,2) were conducted with the baseline slag tank configuration (as described in the previous section) and the combustor at ground potential. The primary objective of these tests was to complete three consecutive collection tank cycles prior to high voltage operation. The tests also allowed an opportunity to establish the baseline slag tank operation prior to making changes to the configuration and/or operation.

Figure 8-9 contains plots of key slag tank parameters during test 91-SREJ-2. In the top plot, both gas thermocouples (A932 and A934) generally read between 1200 and 1500°F throughout the test and are in very good agreement with each other. In the middle plot, the slag tank fill (A931) was maintained at 14 gpm during the first part of the test, and then increased to 17 gpm in an attempt to lower the slag tank water temperature (A933) below 200°F. Note that the water temperature initially decreased in response to this change; however, it was observed to be slowly increasing again near the end of the test. In the bottom plot, the vent line temperature upstream of the quench (A935) remains fairly constant in the 200 to 220°F range, while the vent line temperature downstream of the quench is consistently about 20°F cooler. Following each of the first two tests, post-test inspections were made of the slag tank and vent line. In both cases, the funnel and grinder were clear of slag.

In general, the above operational characteristics of the slag tank (i.e. high slag tank dome temperatures, steady slag tank water and vent line temperatures, and high fill rates) are typically observed during tests in which the vent line has just been cleaned and thus no plugging exists. In this situation, the water level and temperature are well-controlled and the slag tank appears to operate smoothly.

Tests 91-SREJ-1 and 91-SREJ-2 successfully demonstrated the baseline performance of the slag rejection system at zero voltage. The objective of the next several tests was to demonstrate slag rejection system operation at 900 volts (supplied by conductivity power supply), as well as to checkout alternate vent and fill configurations.

Prior to the next test, 91-SEED-1, the vent cap and elbow were removed. This change is shown schematically in Figure 8-10. In the past, most of the vent line plugging has occurred at these two locations. Thus, it was desired to know whether the slag tank could be operated reliably without these two components. As shown in Figure 8-10, the change effectively dropped the inlet of the vent line below the nominal water level. Hence, the gas flow rate through the vent would be expected to be lower relative to the baseline vent configuration, which has inlets for both gas and water.

TABLE 8-2. SUMMARY OF SLAG REJECTOR CHECKOUT TESTS

Test	Date	Duration	Slag Tank Configuration	Test Results
91-SREJ-1 ($\phi_1=0.55$)	4-29-91	87 min (2 starts)	Baseline configuration. Vent cap installed.	All slag tank temperatures within nominal ranges. Both grinder and vent line are clear post-test
91-SREJ-2 ($\phi_1=0.55$)	5-1-91	330 min	Same as above	Same as above
91-SEED-1 ($\phi_1=0.55$)	5-3-91	74 min	Vent cap and elbow removed. Slag tank fill modified to bring inlet closer to center of tank	<ul style="list-style-type: none"> • Low tank gas temps A932 (700-1000°F) A934 (300°F) • High tank water temp (250-400°F) • High vent line temp (230-250°F) • Slag funnel 3/4 full post-test, with large stalactites
91-SEED-2 ($\phi_1=0.55$)	5-7-91	271 min	Vent cap and elbow removed. Baseline fill position	<ul style="list-style-type: none"> • Low gas temps during first half of test, with large fluctuations as tank fills up with slag • High vent line temp (230-250°F) • Slag tank filled with slag from grinder up past water level
91-SEED-3 ($\phi_1=0.60$)	5-9-91	257 min (2 starts)	Same as above	<ul style="list-style-type: none"> • Low gas temperatures (300-800°F) • High tank water temps (200-240°F) • Slag tank funnel completely filled with slag post-test
91-SREJ-3 ($\phi_1=0.55$)	5-15-91	344 min	Baseline configuration. Vent cap reinstalled	<ul style="list-style-type: none"> • All slag tank temperatures within nominal ranges • Both grinder and vent line are clear post-test • Small accumulation of slag on bottom of funnel
91-SREJ-4 ($\phi_1=0.60$)	5-16-91	276 min	Same as above	<ul style="list-style-type: none"> • All slag tank temperatures within nominal ranges • Vent line plugged at isolation hose • Grinder was clear post-test even though vent line plugged

Figure 8-9. Slag Tank Temperatures During 91-SREJ-2 (Baseline Vent Cap)

Figure 8-10. Schematic of Slag Tank - Modified Vent Configuration

The results of test 91-SEED-1 were inconclusive due to the relatively short test duration (74 minutes) as well as the fact that the water fill line was also modified to bring the water outlet close to the center of the slag tank (not shown in Figure 8-10). During the test, gas temperatures were lower than normal, while the tank water and vent line temperatures were significantly higher (230°F and above). Following the test, the slag funnel was observed to be 75% full, completely blocking access to the grinder. Since it could not be determined whether this was caused by the change in vent configuration or the change in fill location, the slag tank water fill line was changed back to its nominal position, while the vent was not changed.

At the start of the next test, 91-SEED-2, the gas temperatures were still below normal (i.e. 600-800°F vs. 1200-1500°F). Slag tank temperatures for this test are plotted in Figure 8-11. At approximately 180 minutes into the test, the gas thermocouples began to behave very erratically, fluctuating between 300 and 1700°F. The tank water thermocouple also became erratic during the same time period. After 270 minutes of operation, the test was shut down, as it was apparent that the slag tank was filling up with slag. After the test, the slag tank was inspected and it was determined that slag had backed up from the slag funnel all the way up past the nominal tank water level.

Initially, the slag plugging was believed to be caused by the large slag stalactites that may have formed on the slag tank neck during a period of low ϕ_1 operation (0.50) that occurred approximately 2 hours into the test. In order to investigate this, the next test, 91-SEED-3, was run at a higher slagging stage equivalence ratio ($\phi_1 = 0.60$). The slag tank temperatures during this test are shown in Figure 8-12. Note that the tank gas thermocouples were still reading below nominal values, at times appearing to be underwater (below 300°F). At approximately 3 hours into the test, the slag tank again showed indications of filling up with slag. The test was subsequently shut down and post-test observations did indeed confirm that the slag funnel was again plugged with molten slag.

Based on the results of 91-SEED-1, -2, and -3, it became clear that the new vent line configuration was principally responsible for the change in slag tank environment and subsequent plugging of the slag funnel and grinder. To confirm this, the original vent cap and elbow were reinstalled and two confirmation tests were run (91-SREJ-3 and 91-SREJ-4). During these tests, the slag tank water and gas temperatures returned to nominal values, while post-test observations indicated that the grinder was clear of slag. Slag tank temperatures from test 91-SREJ-3 are shown in Figure 8-13.

8.2.3 Discussion of Test Results

The above test results demonstrated the importance of maintaining an open, free flowing gas vent during combustor operation. In the four tests conducted with the vent cap installed, no slag accumulation above the grinder was observed. Meanwhile, in all three tests conducted with an underwater vent, the grinder and slag funnel become completely plugged within three hours.

The explanation for this strong correlation is as follows. The lack of a steady gas vent appears to result in the formation of large slag stalactites that grow downward from the slag tap neck. These stalactites periodically break off and fall into the slag tank water. Due to their size and increased terminal velocity through the water, these large slag chunks have not completely cooled by the time they reach the bottom of the funnel. Hence, they remain sticky and then tend to adhere to other slag particles. Soon, these large slag agglomerates bridge over the 8-inch x 12-inch grinder opening and effectively block slag of any size from passing through the system. Once this happens, it is only a matter of time before the slag piles up above the water level and the test must be shutdown.

The presence of a gas vent would be expected to decrease the probability of stalactite formation. First, a small stream of hot combustion gases are drawn into the slag tank, which helps to keep the slag molten as it drips down the slag tap neck into the slag tank. Second, a gas vent prevents steam from rising through the slag tap neck into the combustor, since the pressure in the slag tank is slightly less than the combustor. This prevents steam from cooling the slag as it drips down the neck.

Figure 8-11. Slag Tank Temperatures During 91-SEED-2 (Modified Vent, $\phi_1 = 0.55$)

Figure 8-12. Slag Tank Temperatures During 91-SEED-3 (Modified Vent, $\phi_1 = 0.60$)

Figure 8-13. Slag Tank Temperatures During 91-SREJ-3 (Baseline Vent Cap Reinstalled, $\phi_1 = 0.55$)

Slag tank jacket heat losses and gas temperatures listed in Table 8-3 tend to support the above explanation. For the first two tests that were run with the vent cap installed, 91-SREJ-1 and -2, measured slag tank gas temperatures were in the 1200 to 1500°F range, while slag tank jacket heat losses were in the 100 to 120 Btu/sec range. During 91-SEED-1 and -2, both the gas temperatures and jacket heat losses dropped by 30 to 40%. Both gas temperatures and jacket heat losses again increased back to nominal values when the vent cap was reinstalled (91-SREJ-3). Note also that there appears to be a dependence of jacket heat losses on $\phi 1$. However, based on the results of 91-SEED-3, the increase in slagging stage gas temperature was not enough to make up for the lack of a gas vent, since the slag funnel still became plugged during this test.

Having determined the cause of the slag tank plugging observed during tests 91-SEED-1,2, and 3, it is important to discuss the implications of these results on future vent designs. The need to maintain an open gas vent line is as important as ever. Given the history of vent line plugging at the CDIF (especially during low $\phi 1$ operation), improvements need to be made to ensure that the slag tank can operate reliably and continuously for 25 to 50 hours.

At least three different options have been discussed over the last several months. The first option is to try to improve the current combination gas/water vent to reduce the probability of plugging. This option is probably the easiest to explore in the near term due to the low facility impact. The second option is to install a second gas-only vent so that the functions of gas venting and hot water draining can be separated. This type of venting scheme has been tested both at CTS and Avco/TDS (20 MW_L); however, some additional checkout testing is likely to be required at the CDIF to ensure that slag tank operation is reliable. The third option is to install a redundant gas/water vent at the CDIF that can be activated during a test if the primary vent becomes plugged.

In terms of improving the design of the present gas/water vent, several issues can be addressed. First, the plugging of the vent cap may be primarily caused by the fact that the cap is not actively cooled. Unburned carbon and other floating debris may be cooking along the surfaces of the vent cap, forming a tar-like substance which accumulates and eventually plugs the cap. To check this theory, a water-cooled vent cap should be fabricated and tested at the CDIF.

TABLE 8-3. SLAG TANK JACKET HEAT LOSSES/GAS TEMPERATURES

Test	Date	Slag Tank Configuration	$\phi 1$	Slag Tank Jacket Heat Loss (BTU/SEC)	Slag Tank Gas Temp (A932) (°F)
91-SREJ-1	4-29-91	Vent cap installed.	0.55	100-120	1200-1400
91-SREJ-2	5-1-91	Vent cap installed.	0.55	100-120	1300-1600
91-SEED-1	5-3-91	Vent cap removed. Fill at center of tank.	0.55	70-90	700-1000
91-SEED-2	5-7-91	Vent cap removed. Baseline fill location.	0.55	65-85	800-1000
91-SEED-3	5-9-91	Same as above.	0.60	90-100	300-800
91-SREJ-3	5-15-91	Vent cap reinstalled.	0.55	95-110	1200-1400
91-SREJ-4	5-16-91	Same as above.	0.60	120-140	1200-1400
91-COAL-1	5-17-91	Same as above.	0.55	95-130	1200-1400

Other modifications to the vent line that may decrease the chance of plugging include increasing the inner diameter of the vent line inside the slag tank, increasing the diameter of the vent cap itself, reducing the number of support brackets within the vent cap, decreasing the cross-sectional area of the support brackets, and replacing the current 90° elbow with two 45° bends.

8.2.4 Summary

A series of slag rejector tests were conducted in April-May 1991 to checkout and characterize the operation of the continuous slag rejection system. This section has focused specifically on slag tank operation during this test series. The first two tests were run successfully with the baseline slag tank configuration. The slag tank operated normally with no blockage of either the slag funnel/grinder or vent line. The next three tests were run without the vent cap or adjacent elbow, which have historically been the components in which most of the vent line plugging has occurred. During all three tests, the slag funnel became plugged by large agglomerations of molten slag. The slag plugs were directly caused by a reduction or elimination of gas vent flow due to the modified vent. This was confirmed by reinstalling the original vent cap and running three tests (13 hours total) without any slag plugs.

The slag blockage appears to be caused by the increased formation of slag stalactites in the slag tap neck region due to the lack of a gas vent. With a gas vent, hot combustion gases are drawn into the slag tap, which helps to keep the slag molten as it flows into the tank. Without a gas vent, this hot gas is not drawn in, and instead, steam generated by the quenching of slag may be drawn back out into the combustor. This effect would tend to cool the slag as it enters the tank, increasing the probability of stalactite formation.

The results of the latest test series underscores the need to maintain an open, free flowing gas vent at all times during operation. In the near term, efforts should be made to improve the present gas/water vent line. Possible modifications include actively cooling the vent cap, enlarging the vent cap and vent line diameters, and decreasing the cross-sectional area of the vent cap support brackets. If these efforts are unsuccessful, then either separate gas and water vents should be employed, or a redundant gas/water vent line should be installed.

8.3 ANALYSIS OF PRECOMBUSTOR SLAGGING BEHAVIOR

8.3.1 Introduction/Background

The 50 MW_t coal-fired precombustor (CFPC) was originally installed on the test stand at the CDIF in January, 1989. Prior to this, the CFPC underwent checkout and characterization testing at CTS during 1988. During initial testing, ash and/or slag accumulation in the precombustor components downstream of the PC combustion can was a problem. A schematic of the precombustor is shown in Figure 8-14. Most of the slag accumulation occurred in the filler section, which was initially refractory lined to reduce heat losses. The deposits tended to grow preferentially from the sides and top of the filler section, with the bottom wall of the filler section relatively clean. Also, the typical time required for these deposits to form was relatively short, on the order of 30 minutes to an hour. Based on the above observations, it can be concluded that the deposits were primarily formed by airborne ash and/or slag particles.

During CTS testing, several changes to the CFPC operation (variation of preheat temperature, equivalence ratio) and configuration (elimination of refractory surface, coal injector location, swirl vane opening, baffle diameter, and bypass air mixing plate) were evaluated in order to determine their impact on the CFPC fouling characteristics. In general, none of these changes had a significant impact on the observed fouling characteristics. Finally, the rough wall filler was replaced with a smooth wall, non-slugging section. This resulted in the elimination of porous slag accumulation during short duration tests. From CDIF test 89-CFC-11 (5/15/89) through 91-MATL-3 (11/29/90), over 200 test hours were completed without any significant slag accumulation in the filler section. The longest continuous test was 21.5 hours, with several other tests over 10 hours in length.

More recently, significant slag accumulation in the filler section has been observed post-test on 4 of the past 14 tests. In all cases, a river of molten slag has been observed which originates at the precombustor

Figure 8-14. Precombustor Flow Schematic

combustion chamber, bridges across the transition section, and builds up in the filler section. The new deposits are different from those originally observed in that they are rather dense and molten in nature and usually take longer to develop. At times this growth appears to be self-limiting; however, there have been instances in which a significant portion of the filler cross-sectional area has been blocked, which would have eventually led to shutdown of the test due to an increase in pressure upstream of the slag blockage.

The rate of slag accumulation in the filler section was highest during the most recent test at the CDIF, 91-COAL-1, in which very fine coal was blended with the normal run coal in order to simulate the projected coal particle size distribution during the long duration POC tests. Presently at the CDIF, approximately 20% of the coal is separated as fines during coal processing and disposed of. During longer duration tests, the disposal of a large quantity of fines is expected to be a significant problem, therefore, the current plan is to modify the coal processing system so that the fines can be reincorporated into the run coal and burned in the combustor. In order to ensure that combustor performance and reliability are not significantly affected by the modified coal size distribution, two hot-fired tests have been conducted (90-COAL-1 and 91-COAL-1). For these tests, coal fines were collected over a period of tests, and then blended with the run coal to achieve an approximate blend of 20% fines/80% normal coal. While precombustor operation was not significantly affected during the first coal fines test, significant slag accumulation did occur during the second test, thus prompting the investigation described in the following sections.

8.3.2 Objectives of PC Slagging Behavior Analysis

The primary objectives of the precombustor slagging behavior investigation were to identify the probable cause(s) of the accelerated slagging observed during 91-COAL-1 and to recommend steps that can be taken to solve the problem prior to the long duration POC tests. The investigation proceeded on several fronts.

- 1) A review of CFPC performance and operational characteristics over the last two years of testing was performed in order to identify any changes that have occurred that may have adversely affected CFPC operation.
- 2) Coal particle size distribution from 91-COAL-1 and other tests were analyzed and compared.
- 3) The coal feed system calibration test performed prior to 91-COAL-1 was reviewed.

8.3.3 Review of CFPC Operational Experience

As mentioned above, the CFPC was operated for over 200 test hours without any significant slag accumulation in the filler section following the installation of the smooth wall filler (5/89 thru 11/90). However, gradual changes in CFPC performance and operation appear to have been taking place during this time period that have led to increased slagging activity within the combustion chamber. Table 8-4 highlights some of these operational changes.

The CFPC was originally installed at the CDIF in January, 1989. For the initial tests, the CFPC was configured with a "rough" wall filler with slag retention pins. Porous slag accumulation in the filler section was observed. This accumulation, as was the case during CTS tests, was not self-limiting and led to several combustor shutdowns. Prior to test 89-CFC-11, the CFPC was reconfigured with a smooth wall filler. Plots of PC chamber, transition and filler heat fluxes are shown in Figure 8-15 for test 89-CFC-11. Note that the chamber heat flux is generally over 72 Btu/sec-ft² (200 Btu/sec) throughout the test. Also there are slight bumps in the transition and filler heat flux plots, which can be characterized by a gradual decrease in heat flux followed by a rapid increase. This appears to indicate a steady buildup of slag on surface (slow decrease in heat flux) followed by rapid loss of slag as the deposit either grows too large or is stripped by a change in operating conditions (i.e. coal flow fluctuations). Post-test inspection of the CFPC did not show any significant slag accumulation.

The operation of the precombustor remained very steady and predictable from test 89-CFC-11 (5/89) through test 90-DIAG-13 (2/90). During this time period, approximately 110 hours of coal-fired operation were accumulated. The longest continuous test was 13 hours. Occasionally, slag deposits were observed in the PC combustion can. Slag accumulation in either the transition or filler sections was very rare and never significant in size. The precombustor component heat fluxes were rather predictable, with the PC chamber rarely dropping below 72 Btu/sec-ft². Episodes of slag buildup and subsequent loss were occasionally evident from the transition heat fluxes, and to a lesser extent in the filler section. Thus, while there is little doubt that the combustor can, transition and filler section became partially slagged at times during a test, this process appeared to be self-limiting during this test phase.

The first coal fines test, 90-COAL-1 (11/21/89), was conducted during this time period. As shown in Figure 8-16, component heat fluxes were not significantly different than previous or subsequent tests with the baseline coal. The PC chamber heat flux stayed above 72 Btu/sec-ft² throughout the test, while the transition and filler sections were also at nominal values. No significant slag buildup was evident from the heat flux data and no slag accumulation was noted during post test inspection.

As noted in Table 8-4, a number of changes in precombustor operational behavior have been observed over the last year, starting with test 90-MATL-5. Plots of CFPC component heat losses for this test are shown in Figure 8-17. The "bumpy" heat flux profiles, in which a fast increase in heat flux is followed by a slower decrease, indicate episodes of slag buildup and subsequent slag loss. While this type of behavior had previously been observed occasionally in the transition section, this marked the first time that it had been observed in the combustion chamber. Following the 21.5 hour test, a slag bridge was discovered between the combustor chamber and the filler section.

Another significant CFPC hardware change was made prior to 91-CHEK-1, when the original PC combustion chamber was replaced with one that was plasma sprayed with a thin layer of Inconel 625. In addition, small axial grooves (15 mils deep) were machined into the Inconel layer. The purpose of the change was to determine whether the presence of the axial grooves would affect the slagging behavior of the

TABLE 8-4. SUMMARY OF PRECOMBUSTOR OPERATIONAL HISTORY

Test	Date	Comments
89-CFC-11	5/15/91	<ul style="list-style-type: none"> Smooth wall filler installed, small accumulation on injector sleeve, some slag in can, slag streamer in filler
90-CFC-12 thru 90-DIAG-13	5/89 - 2/90	<ul style="list-style-type: none"> Approximately 110 thermal hours accumulated, longest test was 13 hours, slag occasionally noted in chamber and at base of transition, no noticeable accumulation of slag in filler
90-MATL-1 thru 90-MATL-4	6/90	<ul style="list-style-type: none"> First tests with repaired swirl can, flow orifice pressure taps relocated, no slag accumulation in filler after 13 hours of continuous operation
90-MATL-5	8/12/90	<ul style="list-style-type: none"> Hot-wall filler installed, slag bridge between can and filler after 22 thermal hours, filler heat flux is 15 to 20% lower with evidence of increased slagging
90-CC-4	8/30/90	<ul style="list-style-type: none"> Chamber heat flux begins to fall off more quickly (i.e., 80 to 90 minutes compared to previous 200 to 600 minute response)
90-CHEK-1	11/8/90	<ul style="list-style-type: none"> New combustion can installed with plasma spray surface and axial grooves, chamber slag stripping events become much more frequent, transition events decrease
91-CHEK-2	1/17/91	<ul style="list-style-type: none"> Significant slag accumulation in filler after 4 hours of testing
91-MATL-6	1/29/91	<ul style="list-style-type: none"> 1 to 2-inch thick slag layer on filler bottom after 11 hours of testing
91-MATL-8	2/7/91	<ul style="list-style-type: none"> Small bridge in transition after 3 hours of testing
91-SREJ-2	5/1/91	<ul style="list-style-type: none"> Smooth-wall Inconel filler reinstalled, significant slag accumulation in filler after 6 hours
91-SREJ-3	5/15/91	<ul style="list-style-type: none"> PC coal reduced by 20% as a result of E+H calibration test, transition, filler heat fluxes reduced by 10 to 15%, can heat flux slightly higher with evidence of slag buildup
91-COAL-1	5/17/91	<ul style="list-style-type: none"> Coal fines test, can heat flux drops to 35 Btu/sec-ft² in 20 to 30 minutes, filler has significant slag accumulation post-test

can. Initially, there was no significant differences in PC heat fluxes or post-test observations; however, after approximately 10 to 15 hours of operation, the PC combustion can heat flux began to show signs of increased slagging activity. This is evidenced by slow decreases in heat flux down to 50 to 55 Btu/sec-ft², followed by a rapid increase in heat flux up to 70 Btu/sec-ft². Figure 8-18 shows this characteristic chamber heat flux response during 91-MATL-3.

Prior to 91-SREJ-3, a coal feed system calibration test was performed to determine the coal split between the precombustor and the slagging stage. The results of this test indicated that the precombustor coal had been approximately 20% high, and thus the flow control system was adjusted to supply 20% less coal to the precombustor. During the next two tests, 91-SREJ-3 and 91-SREJ-4, PC combustion can heat fluxes were slightly higher, although the rate of slag stripping appeared to increase. PC component heat fluxes for 91-SREJ-4 are shown in Figure 8-19. Filler heat flux values, on the other hand, were 10 to 15% lower than that measured just prior to the calibration test, which is consistent with the lower coal feed rates to the precombustor.

The final test of the test series involved blending a stream of very fine coal with the normal run coal. The PC heat fluxes for this test are shown in Figure 8-20. The precombustor can heat flux rapidly decreased to half its normal value within 40 minutes of operation. Note that no slag stripping occurred during this time period, indicating that the slag growth, which had previously appeared to be self-limiting, became unstable. The transition and filler heat fluxes were also lower. Post-test, approximately 40% of the

89-CFC-11

DATE: 5 /15 /89

START TIME: 19:24:0

DATA FREQ 30

Figure 8-15. PC Heat Loss Data for Test 89-CFC-11 (First Test with Smooth Wall Filler)

90-COAL-1

DATE: 11/21/89

START TIME: 11:30:0

DATA FREQ 10

Figure 8-16. PC Heat Losses During First Coal Fines Test

Figure 8-17. PC Heat Losses During 90-MATL-5 (First Long Test with "Hot-Wall" Filler)

91-MATL-3

DATE: 11/29/90
START TIME: 15:24:0
DATA FREQ 10

Figure 8-18. PC Heat Losses During 91-MATL-3

91-SREJ-4

DATE: 5 /16 /91
 START TIME: 10:31:8
 DATA FREQ 20

Figure 8-19. PC Heat Losses During 91-SREJ-4

91-COAL-1

DATE: 5 /17 /91
 START TIME: 10 : 39 : 32
 DATA FREQ 15

Figure 8-20. PC Heat Losses During 91-COAL-1

filler cross-sectional area was observed to be blocked, with significant slag accumulation in the precombustor can and transition sections.

Based on the recent history of precombustor slagging behavior, the fact that slag accumulation did occur during the coal fines test was not totally unexpected. What was interesting, however, was the rate at which the PC heat fluxes decreased during the first 30 minutes of the test, indicating an increased slagging rate. Also interesting was the fact that the slag growth appeared to become unstable. The main difference between this test and the previous ones was the combination of a leaner combustion zone (20% less coal) and a significant increase in the amount of fine coal particles (10 microns or less). These two differences are discussed in more detail in the next two sections.

8.3.4 Analysis of Coal Particle Size Distribution

Coal particle size distributions from samples taken during tests 91-SREJ-2, 91-SREJ-4, and 91-COAL-1 are listed in Table 8-5. The samples were analyzed by Babcock and Wilcox Alliance Research Division using a Leeds and Northrup Microtrac analyzer described in Reference 8-2. The sample from 91-SREJ-2 is fairly typical of CDIF tests, i.e. 66% thru 200 mesh. From the 91-SREJ-4 sample it is seen that the coal grind became significantly coarser just prior to 91-COAL-1 (45% thru 200 mesh). When the fines were blended with the normal run coal, the fraction of coal passing through 200 mesh increased to 67%. In addition, the fraction of coal less than 18 microns increased from 9.1% to 27.6%. Thus, the fraction of fine coal was approximately twice as much as normal and three times as much as that burned during the previous test.

8.3.5 Evaluation of Coal Feed System Calibration Test

A detailed evaluation of the coal feed system calibration test performed prior to 91-SREJ-3 is provided in Reference 8-3. This test is critical to understanding subsequent precombustor slagging behavior during 91-COAL-1 since the CFPC coal flow was reduced by 20% as a result of this calibration. The main conclusion from Reference 8-3 is that the calibration procedure has a large degree of uncertainty due to the determination of "actual" precombustor coal flow as the difference of two large load cell readings (total coal and main stage coal). Due to error amplification, the calibration is probably accurate to $\pm 20\%$. Hence, it was recommended that the calibration test be repeated using a more accurate procedure.

8.3.6 Discussion

From the above evidence, it can be concluded that a combination of factors led to the rapid slag accumulation that was observed in the precombustor during 91-COAL-1.

TABLE 8-5. COMPARISON OF COAL PARTICLE SIZE DISTRIBUTIONS

% Passing	Microns	91-SREJ-2 05-01-91 21:30	91-SREJ-4 05-16-91 11:00	91-COAL-1 05-17-91 11:20
50	300	99.4	99.3	99.5
100	150	94.6	77.5	90.4
140	106	81.5	62.3	79.0
200	75	66.4	44.6	67.1
270	53	48.7	31.3	53.9
400	37	35.1	21.1	44.9
500	26	24.8	14.5	37.3
---	18	15.7	9.1	27.6

1. Increased precombustor slagging activity has been observed over the past year. This has been evident from component heat flux behavior and combustor pressure drop measurements during tests, as well as post-test observations. While it is difficult to pinpoint the exact cause, several tests stand out as transition points. After the PC swirl can was repaired following 90-DIAG-13, the chamber heat flux has fallen off during a test at an increased rate. Once this heat flux falls to a certain level, approximately 50 Btu/sec-ft², a portion of the slag that has built up appears to be stripped away. This phenomenon was first observed with regularity during 90-MATL-5, the 21.5 hour test, and has been consistently observed since. The slagging activity in the combustion chamber appeared to have subsided somewhat when the new, plasma-sprayed combustion chamber was installed in November, 1990; however, after about 10 hours, the slagging activity was renewed at an increased pace. During the last six months, significant filler slag accumulation has been observed in 3 out of the last 13 tests (not including the coal fines test).
2. Since 90-MATL-5, the filler heat flux has been about 15 to 20% lower than previous baseline values. At first, this was attributed to the "hot-wall" filler; however, filler heat fluxes are still low since switching back to the baseline Inconel-lined design. This implies either that the filler slags more during operation or that the precombustor coal flow has decreased.
3. Precombustor coal was systematically reduced by 20% prior to 91-COAL-1. This appeared to further increase the slagging rates within the precombustor chamber as evidenced by the chamber heat flux data.
4. Fraction of fine coal particles (less than 18 micron) was increased by a factor of 2 to 3. Although this is not the first time that a coal fines test was conducted, the three factors discussed above were not present simultaneously. According to the calculations presented in Reference 8-4, coal particles less than 18 microns are expected to completely burn out within the available residence time in the PC combustion chamber (10 msec). Thus, increasing the number of fine coal particles by a factor of 2 to 3 would be expected to compound a pre-existing slagging problem.

8.3.7 Summary and Conclusions

A review and analysis of precombustor slagging behavior was performed to determine the cause of the increased slagging rates observed during the coal fines test, 91-COAL-1. From a review of CDIF precombustor heat flux data, it is concluded that a combination of factors led to the rapid slag accumulation observed during this test. First, the slagging rates in the CFPC combustion chamber appear to have been steadily increasing over the past year. Prior to 91-COAL-1, slag accumulation in the filler section was observed in three of the previous thirteen tests. Possible causes are a drift in PC coal flow, change in PC air split, and/or a change in combustion chamber surface characteristics. In addition to this trend, the precombustor coal flow was intentionally lowered 20% based on coal flow calibration test results. This change was made two tests prior to 91-COAL-1 and appeared to further increase slagging rates in the precombustor. Finally, by mixing the fines back in with the run coal, the fraction of fine coal particles (less than 18 micron) was increased by a factor of 2 to 3. Since these small particles are expected to burn out completely within the available residence time in the PC combustion chamber, an increase in fines should would compound a pre-existing slagging problem.

In order to ensure that the precombustor is operated in a non-slagging mode, it is critical that coal and oxidizer flow rates in the combustion can be accurately calibrated. Once the nominal oxidizer-to-fuel mixture ratio has been determined, this value can be varied parametrically to re-establish the baseline non-slagging operating conditions. In addition, the plasma-sprayed combustion can should be replaced with the original Inconel-lined combustion can. After this is accomplished, the coal fines test should be repeated to confirm precombustor operational stability.

8.4 ANALYSIS OF 1A1 SIDEWALL VOLTAGE MEASUREMENTS

8.4.1 Introduction

Voltage distributions were measured on the insulating bar sidewalls of the CDIF 1A1 generator during recent MHD power tests. These data have been analyzed and are reported herein.

Attempts have been made to correlate sidewall voltage behavior with generator operating conditions and with various types of sidebar designs and configurations. The following effects on sidewall voltage distributions have been investigated: 1) the asymmetries in the left- and right-sidewall voltage profiles, 2) the influence of iron oxide injection, and 3) the effects of changes in diagonal generator loading. Attempts have also been made to correlate observed sidewall material wear with interbar voltage measurements.

Data for these investigations were taken during CDIF tests conducted in 1990 and 1991. It should be noted that none of these tests was carried out exclusively for the purpose of investigating sidewall performance. Some of the tests were conducted for current control and inverter checkouts (90-WEST-2, 90-CC-4, 91-CC-1); while others were performed for generator gas-side design and materials confirmation tests (90-MATL-1 through 90-MATL-7, 91-MATL-1 through 91-MATL-6). For this reason, much of the available test data were taken at operating conditions which were not necessarily ideal for sidewall studies, and because of this, some of the behaviors in the sidewall voltage data are still not fully understood.

Most of the CDIF sidewall voltage measurements were from the straight-bar configuration (see Figure 8-21). The prototypical sidewalls of the Integrated Topping Cycle (ITC) are of a Z-bar design. However, some of the conclusions drawn from the straight-bar data analysis are equally valid for the prototypical Z-bar design. This is especially true for surface imposed influences on the sidewall voltage behavior. For example, conclusions concerning surface shorting (interbar shorting) due to excessive iron and/or seed in the slag layers apply to both types of bar designs.

8.4.2 Sidewall Voltage Asymmetry

Two types of asymmetries were noticed in the CDIF sidewall voltage data. One kind of asymmetry is fairly common, appearing in test data from almost every power test and from every channel build. It is characterized by bar elements on opposite sidewalls situating at slightly different potentials. An example of this is shown in Figure 8-22. The other type of voltage asymmetry is less common, occurring only during certain tests or specific portions of a test. It is characterized by bar-to-bar shortings on one of the sidewalls and none on the other. An example of this type of asymmetry is shown in Figure 8-23. The interbar voltages are well distributed on the left wall, while the right wall has the bar-to-bar shortings. The electrical, thermal, and process flow data have been reviewed to identify the probable causes for these skewed sidewall voltage behaviors. These two types of asymmetries are discussed below.

The voltage asymmetry shown in Figure 8-22 does not exist at the beginning of a power test using a refurbished channel. The measured voltage distributions on opposing sidewalls were nearly identical at the start of the 90-WEST-2, 91-CC-1, and 91-CHK-2 tests, all of which had clean and newly rebuilt channels. Figure 8-24 shows typical left and right sidewall voltage profiles when they are symmetric. Based on these results, flow train misalignment can be eliminated as the cause for the sidewall asymmetry. If channel alignment had been the source of the asymmetry, then it should also have appeared at the start of a test with a newly rebuilt channel.

This type of voltage asymmetry usually starts to develop 10 to 30 minutes after the magnet is brought up to full field strength (2.94 T). A typical example of this voltage asymmetry was shown in Figure 8-22. The voltages in Figure 8-22 were measured approximately 40 minutes after those in Figure 8-24. During the intervening time period, the anode-to-anode endbar voltages on one of the sidewalls (the right wall in this example) are reduced from an average of 60 V down to 30 V and the cathode-to-cathode sidebar voltages also decrease slightly. This behavior was observed on all of the instrumented bar frames on the right wall during this test. However, this behavior is not biased to a particular sidewall. In some tests

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Figure 8-21. Comparison of Straight-Bar and Z-Bar Sidewall Designs

Figure 8-22. Asymmetry where Left and Right Sidewall Bar Elements Ride at Different Potentials (from 91-CC-1)

(including the example above) it is the right wall that has the lower anode-to-anode endbar voltages, and in other tests, it occurs on the left wall.

One other observation about this type of voltage asymmetry is that it reappears at the start of a power test if it was present toward the end of the preceding run, with the same channel in place. The patterns and features of the asymmetry found during a test would be very similar to those observed at the end of the preceding test. This behavior suggests that this voltage asymmetry may be caused by dissimilarities in surface properties on the opposing sidewalls. There are two probable causes for this: 1) the slag coverages on the two walls may be slightly different (in terms of slag layer thickness) due to swirling or secondary flow patterns in the channel, and 2) electrical properties of the slag layers on opposing sidewalls may be different due to disparate iron or seed concentrations. Photographs supporting this last explanation are presented in Figure 8-25. These photographs were taken of the disassembled channel after the 90-DIAG-13 test and show the differing amounts of seed deposits (white substance) on the left and right sidewalls. There were substantially more seed deposits on the right wall (near the sidewall-anode corner) than on the left wall. This would, presumably, lead to higher slag electrical conductivity and lower anode-to-anode endbar voltages of the right wall.

The voltage asymmetry characterized by numerous bar-to-bar shortings on one wall and none on the other is shown in Figure 8-23. This behavior clearly suggests that the surface of the shorted wall must be contaminated with seed, iron, or both. This type of asymmetry appeared during 90-CC-4 and 91-MATL-1. The measured data and process flows were examined from these tests to find a possible cause for the observed sidewall shorting. The 90-CC-4 test was conducted in order to checkout the current control devices. The total power test time was only 2.5 hours, during which the generator diagonal loading

Figure 8-23. Asymmetry with Diagonal Shortings on the Right Wall and None on the Left (from 90-CC-4)

Figure 8-24. Typical Comparison of Left and Right Sidewall Voltage Profiles When They are Symmetric (at Start of 91-CC-1)

(inverter loading) was changed several times. The voltage asymmetry persisted over the last 2 hours of the test. A review of the test log showed no indication of seed or iron oxide injection problems during the test. The measured heat losses on the opposing sidewalls were comparable throughout the duration of the test. Any large disparity between the left and right sidewall heat losses would normally imply asymmetric iron oxide injection due to plugged injector ports.

8.4.3 Sidewall Voltage Behavior with Iron Oxide

All of the tests investigated for the present study were conducted with iron oxide addition. Slag doping with iron oxide has proven to be an effective method of reducing cathode wall shorting due to slag polarization. Some general observations on the effects of iron oxide injection on sidewall voltage behavior are reported in this section. The effects of iron oxide injection rates are described in Section 8.4.4.

Of special interest are the long term effects of cathode-side iron oxide injection. In long duration tests with iron oxide injection, it was demonstrated that the cathode wall did not short out (References 8-5 and 8-6), which had been a concern prior to these tests. The cathode wall remained free of slag shortings after more than ten hours of testing. The effects of long term, cathode wall iron oxide injection on sidewall voltage behavior are the subject of the present concern.

There are indications, from the measured sidewall voltage data, that slag resistivity is lowered with time during these extended iron tests. This is especially true in the corner regions, where the sidewalls meet the cathode. In the tests with long duration iron addition (90-DIAG-13 and 91-MATL-6), the values of the cathode-to-cathode sidebar voltages decrease with time. Typically the cathode-to-cathode sidebar insulator gaps would support voltages of the order of 40 volts. In those cases with iron, the voltages at the wall corners would drop in value over time, sometimes to a value as low as a few volts. The intercathode gaps,

Figure 8-25. Photographs of Seed Deposits on the CDIF Aft Sidewalls After the 90-DIAG-13 Test

however, are quite free of shorts. Also, the sidewalls are free of bar-to-bar shorting. All of the interbar voltages are well distributed.

There is, however, occasional evidence of peculiar behavior on the sidewall surfaces. For example, elements within selected diagonal bar frames shorted to the cathode potential in 90-MATL-6, as shown in Figure 8-26. The voltage distributions on the left wall are characterized by the midbars and cathode sidebars both shorting to the cathode potential. On the right wall they are characterized by the cathode sidebar shorting to the cathode potential. It should be noted that the intercathode gaps remain open during this behavior.

Another instance where sidewall shorting was observed and which may have been caused by iron was during the beginning of the 90-DIAG-13 test. Sidebar voltage distributions for this test are shown in Figure 8-27. Here, most of the bars within a diagonal bar frame were shorted to the potential of the anodes. This shorting might be due to excessive iron in the slag layers. During the previous test (90-DIAG-12), iron slurry injection problems were experienced (the iron oxide injection rate was as high as 11 lb/minute on the cathode). Both heat loss data and power output data suggest that one of the sidewalls was contaminated with iron, resulting in much axial current leakage. During the course of the subsequent test (90-DIAG-13), the observed shorting diminished as the excess iron worked its way out of the slag. This trend is shown in Figure 8-28 where the data were taken one hour after that of Figure 8-27.

The CDIF sidewall voltage data analyzed thus far suggests that good long duration iron oxide injection results can be obtained. However, there is sufficient data to show that iron oxide injection is complicated, and that if done improperly, can cause large amounts of sidewall shorting and axial current leakage. More development work is needed to ensure a proper and reliable iron oxide injection system.

8.4.4 Effect of Cathode Wall Iron Oxide Injection Rates on Sidewall Voltage Distributions

The sensitivity of sidewall interbar voltages to various iron oxide injection rates was studied using data from CDIF test 90-DIAG-13. During this test, the sidewall interbar voltage profiles were observed under low (3 to 4 lb/minute), moderate (5 to 6.5 lb/minute), and high (7.5 lb/minute) cathode wall iron oxide injection rates. These data were recorded on the left sidewall near mid-channel, between cathodes 161 and 169.

It was found that the sidewall interbar voltage distribution was generally unaffected by iron oxide when the injection rate was between 3 and 6 lb/minute over a period of 12 hours. There was no indication of significant bar-to-bar shorting occurring at these injection rates suggesting that slurry did not accumulate on the sidewalls.

In one instance, iron oxide injection did influence the sidewall voltage behavior. This occurred when the rate of injection was 7.5 lb/minute, a rate that is higher than that expected during POC testing. In this case, the cathode sidebar-to-cathode electrode gap voltage increased from approximately 35 V to 70 V, when the iron oxide injection rate was increased from 5 lb/minute to 7.5 lb/minute. Figure 8-29 shows a time history of a typical cathode-to-cathode sidebar gap voltage before, during, and after the high iron oxide injection rate. This effect was found to correlate to the increased cathode boundary layer voltage drops during periods of high iron oxide injection. Hence, this sidewall behavior was a gas-dynamic influence (as opposed to a surface influence). Typical time histories of the cathode-wall boundary layer voltage drop and the corresponding iron oxide injection rate are shown in Figure 8-30. This voltage drop data is derived from peg wall transverse voltage measurements at electrode 139. Other voltage drop data upstream from this region show similar behavior during high iron oxide injection rates, indicating that voltage drop is probably elevated throughout the length of the cathode wall. Most likely, the injection of iron oxide at this high rate has caused some of the iron oxide slurry to entrain into the boundary layer, thus quenching the gas in that region and making the boundary layer more resistive.

Figure 8-26. Sidewall Voltage Distributions Early and Late During 90-MATL-6 Showing Increased Cathode-to-Cathode Sidebar Shorting

Figure 8-26. Sidewall Voltage Distributions Early and Late During 90-MATL-6 Showing Increased Cathode-to-Cathode Sidebar Shorting (Continued)

Figure 8-27. Sidebar Voltage Distribution at Beginning of 90-DIAG-13 Showing Anode-to-Anode Sidebar Shorting

Figure 8-28. Sidewall Voltage Distribution 1 Hour after Start of 90-DIAG-13, Showing Decreased Shorting as Iron Oxide on Sidewall from Previous Test Works Its Way Out

Figure 8-29. Time History of Typical Cathode-to-Cathode Sidebar Voltage with High Iron Oxide Injection Rate

Figure 8-30. Time History of Typical Cathode Boundary Layer Voltage Drop with High Iron Oxide Injection Rate

In summary, it would appear that iron oxide injection rates of between 3 lb/minute and 6 lb/minute do not adversely effect sidewall voltage behavior. At abnormally high iron oxide rates, using the present injection technique, there are indications in the data that the iron oxide slurry is getting into the gas instead of spreading on the wall, where it is needed.

8.4.5 Effect of Generator Loading on Sidewall Voltage Distributions

The sensitivity of sidewall voltage behavior to diagonal loading was examined. Sidewall voltage behavior was found to be influenced primarily by changes in the gas potential resulting from generator load changes.

Observations are based on results obtained during CDIF test 90-CC-4. The diagonal load voltage varied between 2.2 and 6.2 kV during the test. The power train was operating at nominal combustor and process flow conditions ($B = 2.92$ T, $N/O = 0.7$, $\phi_1 = 0.55$, $\phi_2 = 0.9$, seed fraction = 1.75% K). The sidewall interbar voltages were measured at cathode locations 161 through 165 on both the left and the right walls.

Figure 8-31 depicts the bar potentials, measured within a diagonal bar frame for 2 different load voltages (all potentials are referenced to the anode wall). The magnitudes of the interbar voltages vary with load voltage. However, the anode-to-anode end bar voltage tends to be higher at the lower load voltage which results in the parallel shift observed in the bar potential data shown in Figure 8-31.

To understand this trend, attempts were made to correlate these bar potentials with the behavior of the gas potential. Figure 8-32 shows gas equipotential curves, projected in the direction of the sidebars (45 degrees from the vertical), as a function of loading. These gas equipotential curves were extrapolated

Figure 8-31. Sidebar Potential Distributions at Various Diagonal Generator Load Voltages

Figure 8-32. Typical Diagonal Gas Equipotential Curves at 2.2 kV and 6.2 kV Load Voltage During 90-CC-4

from vertical peg traverse data recorded at 5 intermediate locations just upstream from the configured sidewall region. It can be seen that both the sidewall bar voltages and the gas potential react similarly to changes in diagonal generator loading. This suggests that the potentials of the sidewall bar elements follow closely the potential of the gas above the wall elements.

The 90-CC-4 interbar voltage data was also used to study the variation in magnitude of the cross-bar voltages, with respect to loading changes, at three critical (wear prone) locations on the sidewalls. Figure 8-33, in addition to illustrating these 3 regions schematically, shows the variation of the measured interbar voltages as a function of loading at the 3 gaps. The data show that these cross-bar voltages, in general, can be reduced with lower load voltages, except for the anode end bar-to-downstream anode region. This cross-bar voltage remained constant, at about -100 volts, regardless of generator loading. One way to reduce the voltage at that gap is to change the geometry of the sidewall bar configuration to more closely align with the gas equipotential curves. Mark VII tests have demonstrated that a Z-bar configuration can effectively accomplish this (Reference 8-7).

In summary, it was found that the behavior of sidewall interbar voltage distributions, during diagonal loading changes, are influenced by the gas potential above the sidewall. Also the cross-bar gap from the anode end bar-to-downstream anode with a straight bar configuration maintains a high magnitude voltage regardless of loading. This situation can be improved by implementing the Z-bar sidewall configuration to align the bars with the equipotential curve.

Figure 8-33. Variation of Interbar Voltages as a Function of Load Voltage for Bare Sidewalls (Based on 90-CC-4)

8.4.6 Comparison of the Effects of Ballast Resistors and Current Controls on Sidewall Voltage Behavior

The effects of ballast resistors versus current controls on sidewall voltage behavior were investigated. The results of this study are somewhat limited in scope due to the restricted number of test conditions from which the data were obtained. The results are discussed below.

The sidewall voltage behavior for channels operated using ballast resistors and current controls were compared. For the purpose of this comparison, test data from CDIF test 90-DIAG-13 provided representative ballast resistor results, while data from the CDIF run 90-CC-4 provided current control results. Both tests were conducted at the nominal combustor/process flow conditions defined earlier and with 4 lb/minute iron oxide injection on the cathode wall. Sidewall voltage comparisons were made for conditions free of cathode nonuniformities. The wired electrode overlap (the number of electrodes which separate the connected anodes and cathodes) for the ballast resistor case was 11, while the overlap for the current control case was 15. The lower number of overlaps for the ballast resistor case accounts for the 6 ohm resistors.

The "external" and "core" flow equipotential angles are defined as $\tan^{-1}(E_y/E_x)$ and $\tan^{-1}(E_{yc}/E_x)$, respectively. The values of E_y are determined from measured Faraday voltages; the values of E_x are estimated from interanode voltage measurements. The values of the Faraday field intensity in the core flow regions, E_{yc} , were inferred from transverse voltage measurements (using peg-style sidewall elements) taken at electrode locations 36, 71, 99, 129, and 136.

Figure 8-34 shows the resulting streamwise gas equipotential angles calculated for the ballast resistor and current control data. In each case the potential angles are measured from the vertical. In addition, the

Figure 8-34. Comparison of Equipotential Angles With Current Controls and Ballast Link Resistors

straight-bar angle is shown. The mismatch of the gas equipotential angles with the bar angle for both diagonal loading conditions, i.e. ballast resistors and current controls, are comparable.

No noticeable differences in sidewall voltage behavior were observed between these two modes of operation except in the time variation of the anode-to-anode sidebar gap voltage. Figure 8-35 shows time histories of this voltage during both tests, at comparable conditions. There were substantially more fluctuations in this voltage during the current control test than during the ballast resistor test. Similar behavior has been noted in Mark VII data. The cause of this difference is under investigation.

8.4.7 Effects of Anode Wall Iron Oxide Injection on Sidewall Voltage Behavior

The consequences of anode iron oxide injection on sidewall voltage distributions were investigated with data obtained during 91-MATL-1 and 91-CC-1. Although previous tests indicated some reduction in anode wall voltage drops with an associated boost in power (possibly due to a reduction in anode wall polarization), the two tests mentioned above showed neither an increase in power nor a clear change in sidewall voltage distribution (Reference 8-8). This result suggests that ferrous anode walls (like the stainless steel clad anodes currently in place at CDIF) will have little or no reaction to anode-side iron oxide addition. Likewise, the sidewall voltage behavior will be insensitive to anode-side iron oxide injection. Noble capped anodes might show changes in sidewall voltages, boundary layer voltage drops, and power, with the addition of anode-side iron oxide.

Figure 8-35. Time Histories of Anode-to-Anode Sidebar With and Without Current Control

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9. TTIRC AND POC INTEGRATION TASK FORCE ACTIVITIES (TASK 8)

The Task 8 activities of the ITC program relate to the operation of the MHD Technology Transfer, Integration and Review Committee (TTIRC) and TRW's role in ensuring the integration of the three POC programs: Integrated Topping Cycle, Integrated Bottoming Cycle and Seed Regeneration Process. The integration function is the responsibility of the POC Integration Task Force.

A meeting of the General Committee of the TTIRC was held on June 17, 1991 at the OMNI Royal Orleans Hotel in New Orleans. The meeting preceded the 29th Symposium on Engineering Aspects of Magnetohydrodynamics (SEAM). Business included discussions regarding seed regeneration options and economics, Western coal test plans at the CFFF, and channel power management for the ITC. In addition, a discussion was lead by Fred Walter of Montana Power regarding utility issues and concerns for MHD commercialization. The meeting concluded with an update on the Clean Coal Technology proposal activities.

A draft of the sixth semi-annual status report (October 90 through March 91) was distributed to the DOE and the TTIRC Executive Committee for review in May. Approval for final distribution is expected in August.

The annual meeting of the Executive Committee is tentatively scheduled for January 1992 in conjunction with the annual DOE MHD Contractors' Review Meeting.

10. PLANNED ACTIVITIES

Task 1

- Maintain the detailed, integrated schedule for the manufacturing phase of the program.
- Release the CADM controlled version of the Interface Document.
- Prepare the Test Plan for the upcoming test series which will checkout the current consolidation cabinet and characterize the PTO and transition regions of the channel.
- Continue to work the interface and integration issues related to the High Voltage Room (HVR) modifications required for the fall test series.
- Continue to analyze and model combustor performance in terms of slag recovery and seed utilization and provide recommendations for future tests at the CDIF.
- Support precombustor flow calibration tests and recommend action to minimize long duration precombustor slagging.
- Evaluate the effect of slag tank modifications on system reliability and control.

Task 2

- Complete manufacturing of all combustor components (cooling panels, pressure shells).
- Assemble the slagging stage exit and air inlet sections, the slagging stage, and the PC end plates.
- Continue the assembly and flow testing of other sections.
- Complete detailed design of the headers, the support stand, and the servicing platforms. Fabrication of the support stand and servicing platforms will be close to completion.
- Complete manufacturing of the manifolds and headers.

Task 3

- Complete fabrication of sidewall elements and initiate assembly of sidewalls.
- Receive material and initiate fabrication of anode electrodes.
- Initiate fabrication of channel inlet frame.

Task 4

- Complete redesign of gas-side surface of selected diffuser segments.
- Complete design and procure materials for aft diffuser.

Task 5

- Proceed with modifications in the High Voltage Room (HVR).
- Build and deliver the current consolidation subsystem diode stack which will be installed in the HVR.
- Test the completed consolidation circuits with the control system in place.

Task 6

- Complete anode cabinet installation, magnet repair, and facility upgrades to the DAS, oxygen system, slag removal system, and high voltage room.
- Initiate testing of slag rejector/removal system and Westinghouse current consolidation cabinet.
- Verify facility operability during 50-hour continuous electrical test.

Task 8

- Complete final distribution of fifth and sixth semi-annual status reports of the MHD TTIRC activities.
- Prepare draft copy of seventh semi-annual status report for distribution to DOE and TTIRC Executive Committee.
- Hold TTIRC Executive Committee meeting in January 1992, in conjunction with the annual DOE MHD Contractor's Review Meeting.

11. SUMMARY

Manufacturing of the slagging stage exit section flat cooling panels, the coal injector hot sleeve, and the precombustor combustion can has been completed. Manufacturing of other exit section cooling panels, the end plate cooling panels and pressure shells is in progress. Welding fixtures were finalized. The design of assembly and shipping fixtures was completed and their manufacturing is close to completion. The procurement of several long lead items for the Low Pressure Cooling System (LPCS) was approved.

Fabrication of channel related prototypical hardware was initiated. The cathode wall fabrication is complete, the sidewall element fabrication is underway, and anode procurements have begun. The sidewall behavior in the Mark VII channel was analyzed in order to provide confirmation for the prototypical sidewall design. Work was also conducted to rectify a potential channel design problem relating to hairline cracks in the caps of the tungsten on tungsten-copper sidewall elements.

Construction of the full-scale Current Consolidation Subsystem continued. All major long lead components have been received and tested to assure conformity to the procurement requirements. Assembly of the lower portion of the power cabinets is complete. Assembly of all SCR and GTO-type switch modules has also been completed.

The primary objective of the test activities at the CDIF was to checkout the operation of the continuous slag rejection system. Other secondary objectives were to look at the effect of seed sweeps, to evaluate different slag tank vent configurations, to recalibrate the Endress + Hauser coal flow meters, and to run a test with fine coal. A total of 31.7 thermal hours were accumulated. There were no power hours during this quarter due the failure of the magnet system during the previous quarter.

In the Combustion Subsystem, efforts were focused on understanding and improving the current levels of slag recovery, and evaluating slag tank and precombustor operation for the purpose of ensuring reliable, long duration operation of each of these components.

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APPENDIX A. CDIF TEST SUMMARIES

The following test summaries were reported for each CDIF test and indicate the testing achievements and the associated problems. A chronological summary report is presented in Tables 7-1 and 8-2. A comprehensive discussion is detailed in Section 8.2.

A.1 SLAG REJECTOR SYSTEM TEST SUMMARIES

A.1.1 91-SREJ-01 and 91-SREJ-02 - Objectives

The primary objective of this test series was to checkout the slag rejector system (provided by TRW and installed by MSE) prior to MHD power or conductivity operations.

A.1.2 91-SREJ-01 - Results - Thermal Time = 1 hour 36 minutes (04/29/91)

- 1) Progressed smoothly through facility startup.
- 2) The slag rejector auto cycle could not make it past the denseveyor refill due to flow switch fluctuations. This is a result of being connected to the quench duct (+2 psig).
- 3) All slag tank temperatures are within nominal ranges. Both grinder and vent line are clear post-test.

A.1.3 91-SREJ-02 - Results - Thermal Time = 5 hours 37 minutes (05/01/91)

- 1) Successful thermal operation with 3 continuous collection tank cycles in automatic. After the first cycle failed, three successful complete cycles in the automatic mode followed.
- 2) Operation of seed oxygen at over 0.5 lb/sec, but maximum seed flow was only 1.5%K.
- 3) Slag in combustion can bridged to filler, but no slag in the first stage air inlet or headend.
- 4) Appeared as though there was good slag recovery, but the slagging of the first stage was poor.

A.2 SLAG REJECTOR SYSTEM/SEED UTILIZATION TEST SUMMARIES

A.2.1 91-SEED-01 through 91-SEED-03 - Objectives

The primary objective of this test series was to checkout the slag rejector system with conductivity prior to MHD power operations. The secondary objectives of this test series included seed utilization studies and operation without a slag tank gas vent.

A.2.2 91-SEED-01 - Results - Thermal Time = 1 hour 27 minutes (05/03/91)

The vent cap and elbow were removed to eliminate the slag tank gas vent. The slag tank water fill was modified to bring the inlet closer to the center of the tank. The results were as follows:

- 1) The coal system plugged at the primary injector screen preventing test objectives from being met.
- 2) Water spray in the slag tank (with inlet spraying vertically) maybe causing erratic readings of slag tank thermocouples and was changed for next test.
- 3) The slag grinder funnel was 3/4 full of stalactites. The reason for this may be due to the center water pipe location or the lack of a slag tank gas vent.
- 4) Conductivity showed channel wiring error - ground to element 280. This was fixed for the next test.
- 5) Slag rejector switching worked with 900 V power supply simulating Hall voltage.
- 6) Low slag tank gas temperatures, high slag tank water temperatures and high vent line temperatures were experienced.

A.2.3 91-SEED-02 - Results - Thermal Time = 4 hours 38 minutes (05/07/91)

Operation continued without a slag tank gas vent. The slag tank water fill inlet was returned to its baseline position. The results were as follows:

- 1) Achieved 3 collection tank dump cycles with the conductivity power supply.
- 2) Coal flow was erratic and E+H corrections indicated that coal went from extremely wet to extremely dry.
- 3) Slag plug approached 1/4 of slag tank volume, extending throughout the dome and down into the grinder funnel. This may have been caused by extended period of low phi operation (from 12:54 to 13:41) due to E+H meter correction or the lack of a gas vent in the slag tank. The slag was molten - same as with 100% slag carry over.
- 4) Obtained some baseline seed data at 1.1%K, 1.7%K, and 2.2%K with the conductivity power supply.
- 5) Low slag tank gas temperatures and high vent line temperatures were experienced.

A.2.4 91-SEED-03 - Results - Thermal Time = 4 hours 28 minutes (05/09/91)

- 1) Slag completely filled the funnel and tank. Big billowy green balls of slag prevented entrance to grinder. Grinder was operating the entire test.
- 2) High temperatures at the beginning of both starts. The precombustor had high coal flow, while the main stage had low coal flow.
- 3) Completed the seed transients (observed gas versus wall seed effects) after 1.1%, 1.75% and 2.4%K.
- 4) Low slag tank gas temperatures and high slag tank water temperatures were experienced.

A.3 CALIBRATION TEST SUMMARY

A.3.1 91-CALB-01 - Objective

The primary objective of this test was to calibrate the coal mass flow meters.

A.3.2 91-CALB-01 - Results - Thermal Time = 48 minutes (05/14/91)

- 1) Calibration data for the E+H (Endress + Hauser) mass flow meters was obtained. Initial data indicates that there was higher coal flow for the precombustor than the E+H meter had indicated.
- 2) No floating slag balls were found in the vent line from the outside vent screen; however, two pieces of slag were trapped.
- 3) Opacity readings of the CDIF stack indicated 20% for CFPC operations which is acceptable under state air quality permit.

A.4 SLAG REJECTOR SYSTEM TEST SUMMARIES

A.4.1 91-SREJ-03 and 91-SREJ-04 - Objectives

The primary objective of this test series was to checkout the slag rejector system (provided by TRW and installed by MSE) prior to MHD power or conductivity operations. As secondary objectives, seed sweeps were initiated and the slag tank vent was returned to the configuration to vent both gas and water.

A.4.2 91-SREJ-03 - Results - Thermal Time = 5 hours 49 minutes (05/15/91)

- 1) Slag funnel/grinder did not plug in approximately 6 hours of thermal operation. This suggested that the slag tank vent line requires a gas vent as well as a water vent for good breakup of slag in the slag tank.
- 2) New correction of the CFPC E+H meter provided 25% less coal to precombustor than previously for the same value read. Combustion can, filler and transition were clean of slag.
- 3) Burner had 3-1/2 ports plugged and was cleaned.
- 4) Automatic cycle of slag rejector kicked out. No resolution as to why, but failed in switching between denseveyor and slag tank.

- 5) Conductivity taken for 4 seed transients with iron oxide and 0.5 lb/sec seed oxygen.
- 6) Slag tank temperatures returned to nominal ranges indicating a gas vent is required for temperature control.

A.4.3 91-SREJ-04 - Results - Thermal Hours = 4 hours 41 minutes (05/16/91)

- 1) No slag plugging in the slag tank even though the slag tank vent hose plugged half way into the test. This continues to confirm that a gas vent in the slag tank is needed.
- 2) Precombustor combustion can, filler and transition are clean of slag. Slight deposition of refractory on precombustor pintle sleeve but not nearly as bad as 91-SREJ-03 test.
- 3) Were able to sweep seed at 1%, 1.7% and 2%K for $\phi_1=0.60$. Conductivity still decreases because heat losses are higher at $\phi_1=0.60$ than at $\phi_1=0.55$.
- 4) Slag weight is 3977 pounds; therefore, there was much greater slag rejection rate when compared to 91-SREJ-03 test at $\phi_1=0.55$.

A.5 FINE COAL TEST SUMMARY

A.5.1 91-COAL-01 - Objective

The primary objective of this test was to checkout the slag rejector system prior to MHD power with fine coal. Coal was supposed to be mixed 20% baghouse coal to 80% normal pulverized coal.

A.5.2 91-COAL-01 - Results - Thermal Hours = 2 hours 36 minutes (05/17/91)

- 1) Finer coal mix lasted for 1-1/2 hours and appeared to have reduced precombustor heat fluxes associated with it. Filler pressure drop increased as slag appeared in transition.
- 2) Returning to nominal coal flow rates with "normal" coal did not allow the transition to become un-clogged. Heat losses were high in the first stage.
- 3) Slag grinder/funnel continued to operate well with combination water/gas vent.

APPENDIX B. SLAG TANK OPERATION

B.1 CURRENT MANUAL OPERATION

The current manual operational sequence is presented as follows (refer to Figure B-1):

- 1) *Fill the slag tank prior to test*
 - a) Operator in test bay opens the valve on the vent line which dumps overboard.
 - b) CCR operator turns on HS-930 which opens pump supply solenoid valve and initiates time delay pump start.
 - c) CCR operator opens FCV-931 for maximum flow (20 GPM+) to slag tank and denseveyor.
 - d) Operator in test bay watches for water to come out of valve. When this occurs, he shuts vent line valve and calls CCR operator.
 - e) CCR operator closes FCV-931 and secures pump (which closes solenoid also).
- 2) *Now at stand-by for MHD/CFC*
 - a) When CFC OFV or CFPC is in operation, or if vent line temperature is greater than 200°F then:
 - operator starts pump
 - operator opens TCV-936 (quench water)
 - b) When the entire CFC is on:
 - operator opens FCV-931 to about 14 GPM
 - operator sets control TIC-936 at 190°F

Normal Occurrence	Operator Action
TC-932 down	Close down FCV-931
TC-932 up	Open FCV-931
TC-936 up	Increase F-938 flow (decrease TCI-936 set point)
TC-936 down	No action
TC-932+FI-938 low	Close FCV-931 and TCV-936 (vent plug)
TC-932+FI-938 high	No action - everything at full flow

- c) At CFC off - operator has to manually shut FCV-931 and TCV-936 and kill pump.

This sequence is highly manually operated and should be made to be automatically controlled. This can be done by placing the appropriate logic in the CDIF programmable logic controller (PLC) that is used for the slag rejector/removal system.

B.2 RECOMMENDED CHANGES TO OPERATION - AUTOMATIC SEQUENCING (SEE FIGURE B-2)

- 1) Include a discrete slag tank fill sequence as follows:
 - a) If slag tank static pressure (A3104 and A3106 and A3107) is less than 15 psia, then initiate fill of the slag tank (turn on HS-930) via FCV-931 at maximum rate.
 - b) Secure flow to the tank when level DP reaches set point.
- 2) Include an automatic slag tank/vent line operational phase located in the PLC as follows:
 - a) If the slag tank static pressure is greater than 20 psia and less than 45 psia, initiate F-938 cool down water flow only, and operate TIC-936 at set point of 190°F. This will prevent the slag tank water level from rising.

- b) If the slag tank static pressure is greater than 45 psia, then initiate F-938 cool down water flow as well as FCV-931 water flow at a preprogrammed rate.
 - c) If vent line "A" (see Figure B-2) shows signs of plugging or other problems, switch to vent line "B" (assuming a second vent line has been incorporated).
- 3) Include an automatic shutdown procedure to cool down the slag tank as follows:
- a) Upon shutdown, automatically dump the denseveyor and collection tank. Keep valves HV-950, HV-951 and HV-952 open, and do not refill the denseveyor.
 - b) Open HV-953 and reinitiate FCV-931 flow. When dome thermocouples indicate inlet water temperature, secure FCV-931 flow, and drain the slag tank by opening HV-949.

B.3 RECOMMENDED CHANGES TO INSTRUMENTATION

Referring to Figure B-2, the additional instrumentation required to support operation is as follows:

- 1) Add DP transmitter for slag tank water level control, and remove the level switch. The transmitter legs should probably have a pressure seal since the slag tank is filled and drained on a recurring basis.
- 2) Add an entire complement of instrumentation for an additional vent line. This includes an upstream thermocouple, a thermocouple downstream of quench, with switchable control of the quench water.
- 3) Add an additional dome gas thermocouple above current location.
- 4) Changing all thermocouples to 1/4 inch for insertion into heavy duty threaded thermowells.

Figure B-2. Recommended CDIF Slag Tank Instrumentation and Operation Schematic

APPENDIX C. SLAG TANK GRINDER AND FUNNEL MODIFICATIONS AND OPTIMIZATION TESTING

C.1 MODIFICATIONS REQUIRED

C.1.1 Grinder Modifications (see Figure C-1)

Test 2:1 grinder tooth ratio (installed during testing this quarter) and 7:1 ratio. This required removal of the grinder and rebuilding it as described in the Operation and Maintenance Manual. After testing, rebuild grinder to either 3:1 or 5:1 ratio for further testing.

C.1.2 Funnel Modification

Replace bottom half bends of funnel with new sloping design shown on Figure C-2.

C.1.3 Slag Tank Modification

Temporarily install a plexiglas door in place of the slag tank door as shown on Figure C-3.

C.2 TEST PLAN

- 1) Baseline (Funnel and 2:1 Grinder Tooth Ratio)
 - a) With grinder and funnel in their normal configuration (as existing), remove the front panel of the funnel and install plexiglas door on the slag tank.
 - b) Fill the slag tank with water, approximately 9 inches above the grinder. Note: the level will be at the top of the slag tank door.
 - c) Drop the underwater light into the slag tank. Tie off and position the light so that it is out of the way and so that it will not interfere with slag dumping or get ground up by the slag grinder.
 - d) With grinder running and light positioned to observe grinding activity, dump a 5-gallon pail half full of slag through the slag tap and record the events and the amount of time it takes for all slag to travel through the grinder and funnel. Each bucket of slag must include two softball size chunks.
 - e) Repeat step d) five times recording times and notes of events (e.g. where did the slag go, does it prefer to stop on funnel lip, etc.).
- 2) 5:1 Grinder Tooth Ratio
 - a) Remove grinder and install a 5:1 tooth ratio for the first test.
 - b) Reinstall grinder and set up to perform test as performed for baseline, including reinstallation of the plexiglas door.
 - c) Repeat steps 1b) through 1e) recording incidents. Note: If this configuration (5:1 tooth ratio) does not work, or works at a slower time than the baseline, continue to step 3) with a 3:1 tooth ratio. If the 5:1 ratio works better than the baseline, continue to step 3) with a 7:1 ratio.
- 3) Modified Grinder Tooth Ratio
 - a) Remove grinder and install tooth ratio required from results of 2c) above (see Figure C-1).
 - b) Reinstall grinder and set up to perform test as performed for baseline, including reinstallation of the plexiglas door.
 - c) Repeat steps 1b) through 1e) recording incidents. Note: Based on this test, the optimum grinder tooth ratio will be established.
- 4) Modified Sloping Funnel with Large Openings
 - a) Remove the grinder and install the funnel modification shown in Figure C-2.
 - b) Install grinder tooth ratio that appeared best in steps 1) through 3) above.
 - c) Repeat steps 1b) through 1e) recording incidents.

Figure C-1. Competing Tooth Spacing for Slag Grinder

Figure C-2. Slag Tank Sloped Funnel Configuration

Figure C-3. Plexiglas Slag Tank Door

C.3 RESULTS CRITERIA

The times and events will be recorded. The following criteria will be used to establish the best configuration:

- 1) Grinder Optimization
 - a) The greatest tooth ratio with the greatest ease in operation.
 - b) The fastest time to "process" the slag in contact with the grinder.
 - c) The least amount of actual grinding.
- 2) Funnel Optimization
 - a) The least interference with slag from the top to the bottom of the grinder horizontal plane.

The best configuration will be installed for the September 1991 MHD testing.

C.4 GRINDER/FUNNEL OPTIMIZATION TESTS

An attempt was made to optimize the slag grinder and the funnel; however, due to limited manpower as well as concurrent CFC reinstallation, the entire test plan was not able to be realized.

C.4.1 Test Configuration

The plexiglas door was installed on the slag tank to facilitate looking into the tank to see how the grinder operates. Using an underwater light as well as lights from the outside of the plexiglas, the grinder was barely perceptible due to the murkiness of the water in the tank, even after several flushes. The best observation was obtained from the slag tap with the underwater light suspended by a string into the water just above the grinder. However, as soon as slag was dumped into the tank, it became impossible to

observe the grinding due to the immediate darkening of the water by the black char in the slag. The only timed comparison that could be observed was with the grinder teeth not underwater.

The only two funnel and grinder configurations that were tested are shown in Figure C-4. Test configuration No. 1 consisted of the flat bottom funnel with 1-1/2 inch diameter holes ($\approx 33\%$ of area for the material to pass through) with a grinder 2:1 tooth ratio with dulled cutter teeth. Test configuration No. 2 consisted of the 45° sloped funnel with 2-inch slots ($\approx 53\%$ area for the material to pass through) with a 7:1 tooth ratio with sharp cutter teeth.

C.4.2 Results

The observations (Table C-1) made as a result of testing these two configurations are as follows:

- 1) When dumping buckets of fine slag containing some large pieces, the large pieces would not make it to the grinder (if not a direct hit) but would become hung up on the configuration No. 1 funnel. However, with the configuration No. 2 funnel, the large pieces would always make it to the grinder.
- 2) With water covering the grinder, the difference between the time for material to pass through the funnel/grinder system in either configuration could not be determined. However, the flat funnel usually had material hung up on it while the angled funnel did not.
- 3) Large (football size) dense slag chunks, saved from dome slagging tests, would not grind but bounced on top of the grinder with either configuration, without being forced through the grinder.
- 4) Softball size porous slag was definitely consumed faster by the grinder with the 7:1 ratio (configuration No. 2) over the 2:1 ratio, but this result may be due to using sharper teeth in configuration No. 2.

Figure C-4. Tested Funnel/Grinder Configurations

TABLE C-1. SLAG GRINDER/FUNNEL TESTING OBSERVATIONS

	Slag dumped into water covering grinder	Large dense slag balls grinding ability	Softball size porous slag balls grinding ability	Maximum size of slag after grinder
Configuration No. 1	Large chunks did not make it to grinder unless a "direct hit" but rested on the flat side of the funnel - small particles proceeded through	Could not grind without weight - bounced on top of cutters	Average 1 minute to grind 2 balls	< 3/8"
Configuration No. 2	No slag hanging up on the funnel - all particles proceeded through funnel to the grinder	Could not grind without weight - bounced on top of cutters	Average 20 seconds to grind 2 balls	< 1-1/4"

- 5) The slag that made it through the 2:1 ratio grinder was < 3/8 inch, while the slag that made it through the 7:1 ratio was < 1-1/4 inch. Problems were not experienced while transferring the larger slag through the slag rejector system. Only buckets of slag were used. It is uncertain if problems will be experienced with larger slag in the slag rejector system.

C.4.3 Conclusions and Recommendations

The 7:1 tooth ratio did not jam, but may produce slag that is too large and could give problems in downstream components. The recommended action is to try out a 5:1 ratio for the 17th quarter testing.

Nothing hung up on the sloped funnel. The recommended action is to keep this configuration for the 17th quarter testing.

The cutter teeth are worn. The recommended action is to hard face them with tungsten-carbide material for enhanced wear properties.

The grinder traps pressure and moisture within the gear and bearing boxes of the grinder. This is due to unequal pressure between rebuilding and operation. The recommended action is to tap each box and install a flex line through the slag tank to the precombustor baffle flanges, ensuring equal pressure in the box and the slag tank at all times.

APPENDIX D. NOMENCLATURE

Abbreviations

1. AIC - Ash Injected Combustor
2. CDIF - Component Development and Integration Facility
3. CDR - Critical Design Review
4. CFC - Coal-Fired Combustor
5. CFPC - Coal-Fired Precombustor
6. CTS - Capistrano Test Site (TRW)
7. DCT - Design Confirmation Test
8. DOE - Department of Energy
9. DVT - Design Verification Test
10. FETS - Fossil Energy Test Site (TRW)
11. GOX - Gaseous oxygen
12. ITC - Integrated Topping Cycle
13. MEF - Material Evaluation Fixture
14. OFV - Oil-Fired Vitiator
15. PDR - Preliminary Design Review
16. POC - Proof-of-Concept
17. PRD - Project Requirements Document
18. PEM - Performance Evaluation Module
19. TTIRC - Technology Transfer, Integration and Review Committee

Symbols

20. β - Beta - Hall parameter
21. δ - Boundary layer thickness (Meters)
22. σ - Plasma Conductivity (Mhos/m) - There are several definitions for plasma conductivity, as follows:
 1. Mid-channel conductivity - the conductivity at the channel mid-point determined experimentally from a plot of conductivity vs. channel axial length. This is the conductivity most often used in presenting test results. Unless otherwise specified, σ refers to this conductivity.
 2. Inlet conductivity - the conductivity at the channel inlet. This parameter can be determined experimentally by extrapolating the conductivity vs. channel length curve to zero.
 3. Bulk conductivity - the conductivity determined in the 1A1 channel at CDIF by taking the voltage drop divided by the current. This parameter is available on-line and is used to spot conductivity changes during testing.
 4. PEM conductivity - the conductivity measured at the Performance Evaluation Module at CTS at subsonic (stagnation) conditions.
23. ϕ_{O1} - Precombustor Equivalence Ratio - Ratio of oxygen input to the coal-fired precombustor combustion chamber to stoichiometric oxygen required for complete combustion of fuels.

24. ϕ_1 - First Stage Equivalence Ratio - Ratio of oxygen input to the first stage to stoichiometric oxygen required for complete combustion of fuels.
25. ϕ_2 - Overall Equivalence Ratio - Ratio of total oxygen inputs to stoichiometric oxygen required for complete combustion of fuels.
26. AR - Aspect Ratio - The height H (anode to cathode distance) divided by the width D (sidewall to sidewall distance) of the channel
27. B - Magnetic field (Tesla)
28. E_x - Axial electric field (volts/m)
29. I_e - Electric current (amps)
30. I_{sc} - Short circuit current (amps)
31. I_x - Axial current (amps)
32. I_{leak} - Constant current leakage that is proportional to the Hall voltage (relating to cathode wall nonuniformities, plasma nonuniformities, and/or voltage drops) (amps).
33. J_y - Faraday current density (amps/cm²)
34. %K - Amount of potassium injected as a percent of total mass flow through power train.
35. L/D - Length -to-hydraulic diameter ratio (second stage)
36. MW_e - Electric megawatts (power output)
37. MW_t - Thermal megawatts (heat input rate)
38. N/O - Molar ratio of nitrogen to oxygen inputs (all input streams).
39. N_{ovlp} - Number of overlapped electrodes in channel.
40. P - electrode pitch (m)
41. P_b - burner pressure (atm)
42. P_{diss} - Power dissipated in ballast resistors (watts)
43. R - Resistance between shorted cathode gaps (ohms/gap)
44. R_{leak} - An end-to-end resistance that is independent of Hall voltage (i.e., current transport through the liquid slag layer) (ohms/gap).
45. R_{link} - Resistance value of link resistor (ohms)
46. T_{250} - Temperature at which slag viscosity equals 250 poise
47. V_{oc} - Open-circuit voltage (volts)
48. ΔV - Transverse voltage drop (e.g., ΔV_{bl} - across boundary layer) (volts)

Definitions

49. Heat Flux - Heat loss per unit area (watts/cm²).
50. Heat Loss - Sensible heat loss to cooling circuits, usually stated as a percent of total thermal input to the combustor.
51. Slag Recovery - Weight of dry slag collected in slag tank as a percentage of dry, SO₃ -free ash fed to the combustor (SO₃ is volatile and is not found in the slag).
52. Weight Percent Oxygen in First Stage (wt. % O₂) - Weight percent of oxygen in vitiated gases entering combustor first stage.

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