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TABLE OF CONTENTS

Executive Summary xi
1. INTRODUCTION 1-1
2. PROJECT DESCRIPTION 2-1
3. SYSTEMS ENGINEERING (TASK 1) 3-1
   3.1 SYSTEM/SUBSYSTEM DOCUMENTATION 3-1
      3.1.1 Interface Documentation 3-1
      3.1.2 Test Plan 3-1
      3.1.3 Facility Impact Report 3-1
      3.1.4 Channel Requirements Document 3-2
      3.1.5 Integrated Schedule Review 3-2
      3.1.6 Contractors' Review Meeting 3-2
4. COMBUSTION SUBSYSTEM DESIGN AND FABRICATION (TASK 2) 4-1
   4.1 COMBUSTION SUBSYSTEM DESIGN ACTIVITIES (SUBTASK 2.1.3) 4-1
      4.1.1 Low Temperature Corrosion and Cooling Water Parameters 4-1
         4.1.1.1 Workhorse Combustor Low Temperature Corrosion Data 4-2
         4.1.1.2 Susceptibility of Prototypical Combustor Materials to Low Concentration Acid Attack 4-5
         4.1.1.3 Recommendations 4-5
      4.1.2 Design Modifications Caused by Low Temperature Cooling Water 4-7
   4.1.3 Manufacturing Development Activities 4-10
      4.1.3.1 Second Stage Brazing 4-10
      4.1.3.2 Welding Parameter Optimization 4-12
      4.1.3.3 Assembly Fixture Design 4-12
   4.1.4 Corrosion Protection During Combustor Manufacturing 4-12
      4.1.4.1 Post-Manufacturing Protection 4-12
      4.1.4.2 Post-Integration Protection 4-16
   4.1.5 Coal Injector Wear Ring Testing 4-16
4.2 COMBUSTION SUBSYSTEM MANUFACTURING (SUBTASK 2.2.1) 4-16
   4.2.1 Prototypical Combustor Manufacturing 4-16
   4.2.2 Low Pressure Cooling Subsystem Procurement 4-17
5. PROTOTYPICAL CHANNEL DESIGN (TASK 3) 5-1
   5.1 1A4 CHANNEL DESIGN AND FABRICATION 5-1
      5.1.1 Summary 5-1
      5.1.2 Introduction 5-2
      5.1.3 1A4 Channel Design 5-2
         5.1.3.1 Nozzle 5-3
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1.3.2 Anode Wall</td>
<td>5-5</td>
</tr>
<tr>
<td>5.1.3.3 Cathode Wall</td>
<td>5-7</td>
</tr>
<tr>
<td>5.1.3.4 Sidewall</td>
<td>5-9</td>
</tr>
<tr>
<td>5.1.3.5 Wiring</td>
<td>5-10</td>
</tr>
<tr>
<td>5.1.3.6 Water Cooling</td>
<td>5-11</td>
</tr>
<tr>
<td>5.1.3.7 Diffuser</td>
<td>5-11</td>
</tr>
<tr>
<td>5.1.3.8 Packaging</td>
<td>5-13</td>
</tr>
<tr>
<td>5.1.3.9 Interfaces</td>
<td>5-13</td>
</tr>
<tr>
<td>5.1.4 Fabrication</td>
<td>5-13</td>
</tr>
<tr>
<td>5.1.4.1 Pre-Fabrication Activities</td>
<td>5-13</td>
</tr>
<tr>
<td>5.1.4.2 Fabrication and Quality Assurance Measures</td>
<td>5-15</td>
</tr>
<tr>
<td>5.1.4.3 Testing</td>
<td>5-16</td>
</tr>
<tr>
<td>5.1.5 Conclusions</td>
<td>5-16</td>
</tr>
<tr>
<td>5.2 1A4 DESIGN CONFIRMATION TESTS AT THE CDIF</td>
<td>5-18</td>
</tr>
<tr>
<td>5.2.1 Anode</td>
<td>5-18</td>
</tr>
<tr>
<td>5.2.2 Sidewalls</td>
<td>5-18</td>
</tr>
<tr>
<td>5.2.3 Cathode</td>
<td>5-20</td>
</tr>
<tr>
<td>5.2.4 Second Stage (Channel Inlet) Frame</td>
<td>5-20</td>
</tr>
<tr>
<td>5.2.5 1A1 Channel Test Results and Discussion</td>
<td>5-20</td>
</tr>
<tr>
<td>5.2.5.1 Anode</td>
<td>5-20</td>
</tr>
<tr>
<td>5.2.5.2 Cathode</td>
<td>5-20</td>
</tr>
<tr>
<td>5.2.5.3 Sidewall</td>
<td>5-20</td>
</tr>
<tr>
<td>5.2.5.4 Channel Inlet Frame</td>
<td>5-22</td>
</tr>
<tr>
<td>5.2.6 1A1 Channel Test: Conclusions</td>
<td>5-22</td>
</tr>
<tr>
<td>5.3 TUBE/PLUG BRAZE INVESTIGATION</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3.1 Summary</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3.2 Background</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3.3 Design</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3.4 Root Cause Investigation</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3.5 Root Cause Finding</td>
<td>5-23</td>
</tr>
<tr>
<td>5.3.6 Corrective Action</td>
<td>5-24</td>
</tr>
<tr>
<td>5.3.6.1 Tube/Plug Materials</td>
<td>5-24</td>
</tr>
<tr>
<td>5.3.6.2 Braze Alloy</td>
<td>5-25</td>
</tr>
<tr>
<td>5.3.6.3 Braze Technique</td>
<td>5-25</td>
</tr>
<tr>
<td>5.3.7 Final Design Selection</td>
<td>5-25</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.8</td>
<td>Tungsten-Copper Base Braze Joint Evaluations</td>
<td>5-26</td>
</tr>
<tr>
<td>5.3.8.1</td>
<td>Hydrostatic Tests</td>
<td>5-26</td>
</tr>
<tr>
<td>5.3.8.2</td>
<td>Wetting and Braze Voids</td>
<td>5-26</td>
</tr>
<tr>
<td>5.3.8.3</td>
<td>Pull Tests</td>
<td>5-26</td>
</tr>
<tr>
<td>5.3.8.4</td>
<td>Corrosion Tests</td>
<td>5-26</td>
</tr>
<tr>
<td>5.3.8.5</td>
<td>Bench-Type Tests</td>
<td>5-26</td>
</tr>
<tr>
<td>5.3.8.6</td>
<td>IA Tests (Build No. 2)</td>
<td>5-26</td>
</tr>
<tr>
<td>5.4</td>
<td>SIDEBAR ATTACK BELOW THE GAS-SIDE SURFACE</td>
<td>5-28</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Summary</td>
<td>5-28</td>
</tr>
<tr>
<td>5.4.2</td>
<td>Nature of Sidewall Wear</td>
<td>5-28</td>
</tr>
<tr>
<td>5.4.3</td>
<td>Solution to Pitting Problem</td>
<td>5-28</td>
</tr>
<tr>
<td>5.4.4</td>
<td>Conclusions</td>
<td>5-28</td>
</tr>
<tr>
<td>5.5</td>
<td>WATER CORROSION: CURRENT STATUS OF 75W25Cu TESTS</td>
<td>5-30</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Background</td>
<td>5-30</td>
</tr>
<tr>
<td>5.5.2</td>
<td>High Heat Flux Test Results</td>
<td>5-33</td>
</tr>
<tr>
<td>5.5.3</td>
<td>Water Corrosion: Conclusions</td>
<td>5-33</td>
</tr>
<tr>
<td>5.6</td>
<td>CHANNEL FABRICATION STATUS</td>
<td>5-34</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Introduction</td>
<td>5-34</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Fabrication Status</td>
<td>5-34</td>
</tr>
<tr>
<td>6.</td>
<td>CURRENT CONSOLIDATION SUBSYSTEM DESIGN AND FABRICATION (TASK 5)</td>
<td>6-1</td>
</tr>
<tr>
<td>6.1</td>
<td>RESISTIVE DIODE STACK CHANGES</td>
<td>6-1</td>
</tr>
<tr>
<td>6.2</td>
<td>DISPLAY SELECTION</td>
<td>6-1</td>
</tr>
<tr>
<td>6.3</td>
<td>MULTIBUS COMPUTER CARDS</td>
<td>6-1</td>
</tr>
<tr>
<td>6.4</td>
<td>PLANNED ACTIVITIES</td>
<td>6-1</td>
</tr>
<tr>
<td>7.</td>
<td>CDIF TESTING</td>
<td>7-1</td>
</tr>
<tr>
<td>7.1</td>
<td>WORKHORSE POWER TRAIN TESTING AT THE CDIF (SUBTASK 6.3)</td>
<td>7-1</td>
</tr>
<tr>
<td>7.1.1</td>
<td>Objectives of Workhorse Test Program</td>
<td>7-1</td>
</tr>
<tr>
<td>7.1.2</td>
<td>Approach</td>
<td>7-2</td>
</tr>
<tr>
<td>7.1.3</td>
<td>Test Summaries</td>
<td>7-2</td>
</tr>
<tr>
<td>7.1.3.1</td>
<td>Accumulation of 50 Electrical Hours on the 1991-Coupon Channel Build No. 1</td>
<td>7-2</td>
</tr>
<tr>
<td>7.1.3.2</td>
<td>Slag Rejector System Tests</td>
<td>7-2</td>
</tr>
<tr>
<td>7.2</td>
<td>CDIF HARDWARE ACTIVITIES</td>
<td>7-6</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Combustion Subsystem Activities</td>
<td>7-6</td>
</tr>
<tr>
<td>7.2.1.1</td>
<td>Low Temperature Acid Corrosion Investigation</td>
<td>7-6</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

7.2.1.2 Second Stage 7-7
7.2.1.3 Main Stage Coal Pintle 7-8
7.2.1.4 Precombustor Coal Pintle 7-8
7.2.1.5 Headend Plate 7-8
7.2.2 Channel Hardware Activities 7-8
7.2.3 Slag Rejenerator Activities 7-10
7.2.4 CDIF System Activities 7-12
    7.2.4.1 Primary Cooling Water System 7-12
    7.2.4.2 Iron Oxide System 7-14
    7.2.4.3 Coal System 7-14
    7.2.4.4 Seed System 7-15
    7.2.4.5 Magnet 7-15
7.3 TEST PLANS 7-15
8. MODELING AND PERFORMANCE ANALYSIS ACTIVITIES (SUBTASK 1.3) 8-1

8.1 EVALUATION OF CHANNEL WALL SLAGGING 8-1
    8.1.1 Nominal Channel Heat Fluxes 8-2
    8.1.2 Effect of Seed Addition on Channel Heat Fluxes 8-6
    8.1.3 Individual Anode Coupon Heat Fluxes 8-9
    8.1.4 Summary/Conclusions 8-11
8.2 ANALYSIS OF 1A1 SIDEWALL VOLTAGE MEASUREMENTS 8-11
    8.2.1 Introduction 8-11
    8.2.2 General Observations 8-11
    8.2.3 Plasma Equipotential/Wall Angle Differences 8-15
    8.2.4 Sidewall-to-Anode Voltage Differentials 8-20
    8.2.5 Effect of Sidewall Jumpers on Sidewall-to-Anode Voltage Differentials 8-26
    8.2.6 Summary/Conclusions 8-28
8.3 MARK VII INVESTIGATION FOR THE 1A4 SEGMENTED DIFFUSER 8-29
    8.3.1 Summary 8-29
    8.3.2 Analytical Model of Unloaded Rear Channel Section 8-29
        8.3.2.1 Introduction 8-29
        8.3.2.2 General Model 8-29
        8.3.2.3 Model Applied to the 1A1 Rear PTO Section 8-31
        8.3.2.4 Solution of 1A1 Unloaded Rear Section Using the Model 8-31
    8.3.3 Mark VII Investigation of Unloaded Rear Channel Section 8-33
        8.3.3.1 Introduction 8-33
TABLE OF CONTENTS (Continued)

8.3.3.2 Test Configuration 8-33
8.3.3.3 Test Results: Barewall 8-35
8.3.3.4 Test Results: Slagged 8-36
8.3.3.5 Comparison of Experimental Data with Analytical Predictions 8-36

9. TTIRC AND POC INTEGRATION TASK FORCE ACTIVITIES (TASK 8) 9-1
10. PLANNED ACTIVITIES 10-1
11. SUMMARY 11-1
12. QUARTERLY REPORT DISTRIBUTION LIST 12-1
APPENDIX A. CDIF TEST SUMMARIES A-1
   A.1 LONG DURATION TEST SUMMARIES: 1991-COUPON CHANNEL BUILD NO. 1 A-1
      A.1.1 91-MATL-07 through 91-MATL-08 - Objectives A-1
      A.1.2 91-MATL-07 - Results (02/05/91) A-1
      A.1.3 91-MATL-08 - Results (02/07/91) A-1
   A.2 SLAG REJECTOR SYSTEM TEST SUMMARY A-1
      A.2.1 91-SREJ-01 - Objectives A-1
      A.2.2 91-SREJ-01 - Results (04/29/91) A-1

APPENDIX B. NOMENCLATURE B-1
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1</td>
<td>Air Inlet Filler</td>
<td>4-2</td>
</tr>
<tr>
<td>4-2</td>
<td>Top Plate Corrosion (91 Hours Firing Time, 4000 Hours Downtime)</td>
<td>4-3</td>
</tr>
<tr>
<td>4-3</td>
<td>Bottom Plate Corrosion (91 Hours Firing Time, 4000 Hours Downtime)</td>
<td>4-4</td>
</tr>
<tr>
<td>4-4</td>
<td>Filler Coupon Layout</td>
<td>4-8</td>
</tr>
<tr>
<td>4-5</td>
<td>Prototypical Cooling Panel</td>
<td>4-9</td>
</tr>
<tr>
<td>4-6</td>
<td>Standard Panel Penetration</td>
<td>4-10</td>
</tr>
<tr>
<td>4-7</td>
<td>347 Stainless Steel Hardware in Precombustor</td>
<td>4-11</td>
</tr>
<tr>
<td>4-8</td>
<td>Initial and Final Plug Weld Geometry</td>
<td>4-14</td>
</tr>
<tr>
<td>4-9</td>
<td>Slag Dump Section Assembly Fixture</td>
<td>4-14</td>
</tr>
<tr>
<td>4-10</td>
<td>Air Inlet Exit Section Assembly Fixture</td>
<td>4-15</td>
</tr>
<tr>
<td>4-11</td>
<td>Schematic of Flow Cart for Panel Corrosion Protection</td>
<td>4-15</td>
</tr>
<tr>
<td>5-1</td>
<td>1A4 Channel, Nozzle and Diffuser in Magnet Bore</td>
<td>5-3</td>
</tr>
<tr>
<td>5-2</td>
<td>1A4 Channel Top View, Cross-Section and Side View on Strongback</td>
<td>5-4</td>
</tr>
<tr>
<td>5-3</td>
<td>Cross-Section of 1A4 Channel Showing Materials of Construction, Wiring, Hosing, Manifolding and Fit in the Magnet Bore</td>
<td>5-4</td>
</tr>
<tr>
<td>5-4</td>
<td>1A4 Channel Corner Assembly Detail</td>
<td>5-5</td>
</tr>
<tr>
<td>5-5</td>
<td>1A4 Anode Bars</td>
<td>5-6</td>
</tr>
<tr>
<td>5-6</td>
<td>Orientation in Tungsten Cap Laminations for Anodes</td>
<td>5-6</td>
</tr>
<tr>
<td>5-7</td>
<td>1A4 Channel Anode Wall Fault Protection. Arc Stretching Gap on Anodes and G-7 Liner</td>
<td>5-7</td>
</tr>
<tr>
<td>5-8</td>
<td>1A4 Anode Wall Cap Segmentation and Layout</td>
<td>5-8</td>
</tr>
<tr>
<td>5-9</td>
<td>1A4 Cathode Bars</td>
<td>5-8</td>
</tr>
<tr>
<td>5-10</td>
<td>1A4 Channel Sidewall Gas-Side Material Zone Layout</td>
<td>5-9</td>
</tr>
<tr>
<td>5-11</td>
<td>1A4 Sidewall Z-Bar Elements</td>
<td>5-10</td>
</tr>
<tr>
<td>5-12</td>
<td>1A4 Electrode Wall Cooling Scheme</td>
<td>5-11</td>
</tr>
<tr>
<td>5-13</td>
<td>1A4 Sidewall Cooling Scheme</td>
<td>5-12</td>
</tr>
<tr>
<td>5-14</td>
<td>Supersonic Diffuser, Segmented Section</td>
<td>5-12</td>
</tr>
<tr>
<td>5-15</td>
<td>Iron Oxide Injection Slurry Bar</td>
<td>5-14</td>
</tr>
<tr>
<td>5-16</td>
<td>Typical Channel Subassembly Work Flow Logic</td>
<td>5-17</td>
</tr>
<tr>
<td>5-17</td>
<td>Location and Configuration of Right Forward Sidewall Z-Bar Coupons</td>
<td>5-19</td>
</tr>
<tr>
<td>5-18</td>
<td>Cross-Sections of Sidewall Test Elements</td>
<td>5-19</td>
</tr>
<tr>
<td>5-19</td>
<td>Typical Row of Z-Bar Elements Subsequent to 20 Test Hours</td>
<td>5-22</td>
</tr>
<tr>
<td>5-20</td>
<td>Photograph Showing Region of Braze-to-Tube Interface Corrosion</td>
<td>5-24</td>
</tr>
<tr>
<td>5-21</td>
<td>Photograph Showing Cross-Section of Tungsten-Copper Plugs Brazed into Tungsten-Copper Base Elements using Handy and Harman B505 Braze Alloy</td>
<td>5-25</td>
</tr>
<tr>
<td>5-22</td>
<td>Photographs Showing Cross-Section of Brass Tube Brazed into Tungsten-Copper Base Element with Handy and Harman B505 Braze Alloy</td>
<td>5-27</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES (Continued)**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-23</td>
<td>Pitting on Prototypical Sidewall Element</td>
<td>5-29</td>
</tr>
<tr>
<td>5-24(a)</td>
<td>Schematic of Left Sidewall and Water Leaks</td>
<td>5-29</td>
</tr>
<tr>
<td>5-24(b)</td>
<td>Schematic of Right Sidewall and Water Leaks</td>
<td>5-30</td>
</tr>
<tr>
<td>5-25</td>
<td>Scanning Electron Microscope Picture of Pitted Sidebar</td>
<td>5-31</td>
</tr>
<tr>
<td>5-26</td>
<td>Scanning Electron Microscope Advanced Imaging Material Analysis at the Pitted Surface</td>
<td>5-32</td>
</tr>
<tr>
<td>5-27</td>
<td>Channel and Diffuser Fabrication Schedule</td>
<td>5-35</td>
</tr>
<tr>
<td>5-28</td>
<td>Channel and Diffuser Fabrication Schedule (Continued)</td>
<td>5-36</td>
</tr>
<tr>
<td>6-1</td>
<td>Upstream Power Takeoff Region: 3/19/91</td>
<td>6-2</td>
</tr>
<tr>
<td>7-1</td>
<td>Measurements of pH in Various Locations of the Combustor at the CDIF</td>
<td>7-7</td>
</tr>
<tr>
<td>7-2</td>
<td>CFC Second Stage Configuration - CDIF - 50SS - 910107</td>
<td>7-9</td>
</tr>
<tr>
<td>7-3</td>
<td>Schematic of Main Stage Coal Pintle Indicating Where Erosion Resistant Material is Utilized</td>
<td>7-10</td>
</tr>
<tr>
<td>7-4</td>
<td>Slag Rejection System Schematic</td>
<td>7-11</td>
</tr>
<tr>
<td>7-5</td>
<td>Coupon Flow Test Schematic</td>
<td>7-13</td>
</tr>
<tr>
<td>7-6</td>
<td>Water Corrosion Coupon Test Report</td>
<td>7-14</td>
</tr>
<tr>
<td>7-7</td>
<td>ITC CDIF Test Schedule as of 04/22/91</td>
<td>7-16</td>
</tr>
<tr>
<td>8-1</td>
<td>Anode Wall Heat Flux Response to Seed Flow Initiation</td>
<td>8-7</td>
</tr>
<tr>
<td>8-2</td>
<td>Cathode Wall Heat Flux Response to Seed Flow Initiation</td>
<td>8-8</td>
</tr>
<tr>
<td>8-3</td>
<td>Left Sidewall Heat Flux Response to Seed Flow Initiation</td>
<td>8-8</td>
</tr>
<tr>
<td>8-4</td>
<td>Right Sidewall Heat Flux Response to Seed Flow Initiation</td>
<td>8-9</td>
</tr>
<tr>
<td>8-5</td>
<td>Anode Coupon Heat Flux Results</td>
<td>8-10</td>
</tr>
<tr>
<td>8-6A</td>
<td>Schematic of Right Z-Wall Configuration</td>
<td>8-12</td>
</tr>
<tr>
<td>8-6B</td>
<td>Schematic of Left Z-Wall Configuration</td>
<td>8-12</td>
</tr>
<tr>
<td>8-7</td>
<td>Observed Wear Patterns on the CDIF Sidewalls</td>
<td>8-13</td>
</tr>
<tr>
<td>8-8A</td>
<td>Sidewall Voltage Instrumentation - Z-Bar Right Sidewall</td>
<td>8-13</td>
</tr>
<tr>
<td>8-8B</td>
<td>Sidewall Voltage Instrumentation - Z-Bar Left Sidewall</td>
<td>8-14</td>
</tr>
<tr>
<td>8-8C</td>
<td>Sidewall Voltage Instrumentation - Forward Right Sidewall</td>
<td>8-14</td>
</tr>
<tr>
<td>8-8D</td>
<td>Sidewall Voltage Instrumentation - Aft Right Sidewall</td>
<td>8-15</td>
</tr>
<tr>
<td>8-9A</td>
<td>Typical Sidewall Voltage Distribution - Z-Wall</td>
<td>8-16</td>
</tr>
<tr>
<td>8-9B</td>
<td>Typical Sidewall Voltage Distribution - Z-Wall</td>
<td>8-17</td>
</tr>
<tr>
<td>8-9C</td>
<td>Typical Sidewall Voltage Distribution - 4-Segment Bar Wall</td>
<td>8-18</td>
</tr>
<tr>
<td>8-9D</td>
<td>Typical Sidewall Voltage Distribution - 3-Segment Bar Wall</td>
<td>8-19</td>
</tr>
<tr>
<td>8-10</td>
<td>Comparison of Straight Diagonal Wall and Z-Wall for the Same Overlap Angle</td>
<td>8-20</td>
</tr>
<tr>
<td>8-11</td>
<td>Resultant Electric Field and Gap Voltage as a Function of Plasma and Wall Angle Differences</td>
<td>8-21</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES (Continued)**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-12</td>
<td>Comparison of 1A4 Sidewall Bar Angle with Calculated Plasma Equipotential Angle</td>
<td>8-21</td>
</tr>
<tr>
<td>8-13</td>
<td>Effect of Boundary Layer Voltage Profile on Sidewall-to-Anode Voltage</td>
<td>8-22</td>
</tr>
<tr>
<td>8-14A</td>
<td>Example of a &quot;Case A&quot; Boundary Layer Voltage Profile</td>
<td>8-23</td>
</tr>
<tr>
<td>8-14B</td>
<td>Example of a &quot;Case B&quot; Boundary Layer Voltage Profile</td>
<td>8-24</td>
</tr>
<tr>
<td>8-14C</td>
<td>Example of a &quot;Case C&quot; Boundary Layer Voltage Profile</td>
<td>8-24</td>
</tr>
<tr>
<td>8-15</td>
<td>Example of Time History Plots for &quot;High&quot;, &quot;Medium&quot;, and &quot;Low&quot; Sidewall-to-Anode Voltages</td>
<td>8-25</td>
</tr>
<tr>
<td>8-16</td>
<td>Schematic of Sidewall Elements Jumpered to Their Upstream Anodes</td>
<td>8-26</td>
</tr>
<tr>
<td>8-17</td>
<td>Location of Sidewall Jumpers Installed for Tests 91-MATL-5 Through 91-MATL-8</td>
<td>8-27</td>
</tr>
<tr>
<td>8-18</td>
<td>Electrical Model of a Generic Unloaded Channel Segment</td>
<td>8-30</td>
</tr>
<tr>
<td>8-19</td>
<td>Schematic of Positive Inverter Buss Potential</td>
<td>8-33</td>
</tr>
<tr>
<td>8-20</td>
<td>Calculated Potentials on the 1A1 Channel with the Last Eight Electrodes Floating</td>
<td>8-34</td>
</tr>
<tr>
<td>8-21</td>
<td>Test Configuration of the 1A1 Rear PTO Region with the Last Eleven Anodes Floating</td>
<td>8-34</td>
</tr>
<tr>
<td>8-22</td>
<td>Comparison of Analytical Model to CDIF 1A1 Data</td>
<td>8-35</td>
</tr>
<tr>
<td>8-23</td>
<td>Schematic of the Mark VII Channel Configured for Rear Bleed Resistor Tests</td>
<td>8-36</td>
</tr>
<tr>
<td>8-24</td>
<td>Interelectrode Voltages on the Mark VII: Barewall, Matched Load, All Bleed Resistors Open</td>
<td>8-37</td>
</tr>
<tr>
<td>8-25(a)</td>
<td>Interelectrode Voltages on the Mark VII: Barewall, Open Circuit, Ramped Bleed Resistor Profile</td>
<td>8-38</td>
</tr>
<tr>
<td>8-25(b)</td>
<td>Interelectrode Voltages on the Mark VII: Barewall, Short Circuit, Ramped Bleed Resistor Profile</td>
<td>8-39</td>
</tr>
<tr>
<td>8-26</td>
<td>Interelectrode Voltages on the Mark VII: Slagged, Matched Load, All Bleed Resistors Open</td>
<td>8-40</td>
</tr>
<tr>
<td>8-27</td>
<td>Comparison of Analytical and Measured Gap Voltages on the Mark VII Floating Electrodes under Barewall Conditions and Open Bleed Resistors</td>
<td>8-42</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>2-1</td>
<td>MHD ITC Task Objectives</td>
<td>2-2</td>
</tr>
<tr>
<td>4-1</td>
<td>100°F Corrosion Test Data With Sulfuric Acid</td>
<td>4-5</td>
</tr>
<tr>
<td>4-2</td>
<td>100°F Corrosion Test Data With Nitric Acid</td>
<td>4-6</td>
</tr>
<tr>
<td>4-3</td>
<td>200°F Corrosion Data</td>
<td>4-6</td>
</tr>
<tr>
<td>4-4</td>
<td>Braze Development Test Matrix</td>
<td>4-11</td>
</tr>
<tr>
<td>4-5</td>
<td>Weld Qualification Test Matrix</td>
<td>4-13</td>
</tr>
<tr>
<td>4-6</td>
<td>Low Pressure Cooling System Operating Parameters</td>
<td>4-18</td>
</tr>
<tr>
<td>4-7</td>
<td>Low Pressure Cooling System (LPCS) Procurement Schedule</td>
<td>4-18</td>
</tr>
<tr>
<td>5-1</td>
<td>Measured Wear Data and Projected Lifetimes of Z-Bar Sidewall Elements</td>
<td>5-21</td>
</tr>
<tr>
<td>7-1</td>
<td>CDIF Testing - 15th Quarter - Summary Report</td>
<td>7-3</td>
</tr>
<tr>
<td>7-2</td>
<td>1991-Coupon Channel 50-Hour Electrical Test Series</td>
<td>7-4</td>
</tr>
<tr>
<td>7-3</td>
<td>1991 Slag Rejcctor Checkout Test</td>
<td>7-5</td>
</tr>
<tr>
<td>7-4</td>
<td>CDIF PCW W/Cu Coupon Corrosion Results (4/15/91)</td>
<td>7-13</td>
</tr>
<tr>
<td>8-1</td>
<td>CDIF Tests Included in Channel Wall Slagging Study</td>
<td>8-2</td>
</tr>
<tr>
<td>8-2</td>
<td>Heat Fluxes at Start of Test (W/cm²)</td>
<td>8-3</td>
</tr>
<tr>
<td>8-3</td>
<td>Heat Fluxes During Steady State with No Power (W/cm²)</td>
<td>8-4</td>
</tr>
<tr>
<td>8-4</td>
<td>Heat Fluxes During Steady State with Power On (W/cm²)</td>
<td>8-5</td>
</tr>
<tr>
<td>8-5</td>
<td>Comparison of Average Sidewall Gap Voltage With and Without Jumpers Installed</td>
<td>8-27</td>
</tr>
</tbody>
</table>
EXECUTIVE SUMMARY

This fifteenth quarterly technical progress report of the MHD Integrated Topping Cycle Project presents the accomplishments during the period February 1, 1991 to April 30, 1991. A summary of the work completed during this reporting period is presented in this Executive Summary.

SYSTEMS ENGINEERING (SECTION 3)

The Facility Impact Report, a document used to transmit requirements placed on the facility by the prototypical hardware, was released. The Interface Document was also released as an Appendix to this report. The Interface Document includes all of the CDR comments and accounts for the removal of the HPCS and the subsequent addition of the LPCS.

The High Voltage Room requirements for the September reconfiguration were finalized.

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

Program personnel attended the annual Contractors' Review Meeting.

COMBUSTION SUBSYSTEM DESIGN AND FABRICATION (SECTION 4)

Based on hardware inspection and acid corrosion test results, a 110°F cooling water temperature (with 200°F dryout capabilities) was selected for the Low Pressure Cooling System (LPCS).

Design modifications (such as Inconel 625 overlaying of the cooling panel edges) were incorporated to protect the non-gas facing surface of the components from low temperature corrosion.

Purchase orders were placed for the combustor cooling panels, slagging stage baffle, and pressure shells. Vendor manufacturing shop planning documents are being reviewed. Second stage hardware manufacturing is in progress.

Negotiations for the design and fabrication of the Low Pressure Cooling System were completed.

PROTOTYPICAL CHANNEL DESIGN (SECTION 5)

Final design of an MHD channel for the ITC program POC test has been completed. The channel was designed to be capable of 1.5 MWₑ power output and a lifetime of 2000 hours. Emphasis was placed upon durability and reliability. Hence, specific measures were taken to design against channel damage due to electric faults. The life-limiting issues associated with electrochemical corrosion and erosion of gas-side surfaces were addressed by the use of various materials with proven wear characteristics in a coal-fired MHD channel environment.

Work was also conducted to identify and rectify potential problem areas in the channel design including: 1) leaky water tubes, 2) pitting on sidewall coupons, and 3) water-side corrosion. Some of the water tube elements that were installed in the 1A1 workhorse channel leaked. The problem was attributed to interface corrosion between the braze joint and stainless steel tube resulting from the braze process. This difficulty was overcome by the use of a different braze alloy and change in the tube and plug materials. The new tube material choice was brass, and the plug was made from tungsten-copper. Pitting of prototypical sidewall coupons was observed in the CDIF workhorse testing. The most likely cause of the observed pitting, water leaks resulting from cooling water tube braze failures, has been remedied. New brazing procedures and isolation of the sidebar gas-side material from water contact will prevent sidebar pitting in the prototypical channel. Water-side corrosion tests reported in this quarterly report include the latest results of tungsten-copper elements at controlled pH, heat flux and voltage levels.
CURRENT CONSOLIDATION SUBSYSTEM DESIGN AND FABRICATION (SECTION 6)

The activities of this quarter dealt exclusively with the material procurement and construction of the full scale CDIF Current Consolidation Subsystem for the anode electrodes. The equipment is being built as specified in the CDR document. No significant changes have been made in the design.

CDIF TESTING (SECTION 7)

Test activities during this quarter were divided into two distinct test series: 1) accumulation of electrical hours on the prototypical channel elements which had been installed in the workhorse 1A1 channel, and 2) checkout of the operation of the continuous slag rejection system. A total of 5.2 thermal hours and 2.5 electrical hours were accumulated during this reporting period.

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

1) Evaluation of low temperature acid corrosion during combustor operation and downtime.
2) Inspection of second stage combustor components in order to determine the susceptibility to corrosion of the various braze alloys and stainless steel cladding materials currently in service.
3) Inspection of the wear characteristics of the main stage coal injector.
4) Installation of Phase II of the continuous slag rejector project which provided the controls and instrumentation necessary for continuous slag rejection.
5) Removal and inspection of the prototypical anode and sidewall channel elements. The sidewall elements were repaired (coolant tubes/plugs rebrazed) or replaced by Avco/TDS. The sidewall and anode elements were reinstalled in the 1A1 workhorse channel at the end of the quarter.

MODELING AND PERFORMANCE ANALYSIS ACTIVITIES (SECTION 8)

In the combustion subsystem, efforts continued to focus on understanding and improving the current levels of slag recovery and seed utilization achieved by the combustor. Analytical support was also provided in the areas of slag rejection system operation, precombustor operation, and oil burner design modification.

Channel data analysis activities continued in support of prototypical coupon testing at the CDIF. Analyses are presented on channel wall slagging behavior and sidewall voltage distributions.

To predict the electrical behavior of the unloaded diffuser segments, an analytical model was developed for a generic unloaded region at the back of an MHD channel. An investigation was carried out on the Mark VII workhorse channel to examine the effect of various bleed resistor profiles on an unloaded rear section of the channel.

TTIRC (SECTION 9)

A meeting of the Executive Committee of the TTIRC was held on February 21, 1991 at the Pittsburgh Westin William Penn Hotel in conjunction with the annual DOE MHD Contractors' Review Meeting. Business included updates from the three POC programs with a special emphasis on test plan consistency, seed regeneration economics and Western coal options, status of the Clean Coal Technology proposal, and DOE action regarding POC task force program recommendations.

SCHEDULE

The overall schedule for the ITC project is shown on the following pages.
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 MWt) slagging coal combustion subsystem. Avco 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 MWt 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 MWt Combustor Design, Fabrication, and Shipment
Task 3  50 MWt 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 Fifteenth Quarterly Technical Progress Report covers the period February 1, 1991 to April 30, 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 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. The CDR was held for the current consolidation subsystem, and a wrap-up CDR was held to complete the remaining issues from the initial channel subsystem design review. The subcontract for the design and fabrication of the low pressure cooling system was placed. Fabrication of prototypical hardware was initiated this quarter. 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

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SYSTEMS ENGINEERING STUDIES (TASK 1)</strong></td>
<td>Perform power train/facility integration activities to ensure compatibility of topping cycle components with the existing test bay at the CDIF. Define system level requirements and specifications for the integrated topping cycle power train. Provide test planning and performance data analysis support for CDIF power train testing.</td>
</tr>
<tr>
<td><strong>PROTOTYPICAL 50 MW&lt;sub&gt;t&lt;/sub&gt; COMBUSTOR DESIGN, FABRICATION, AND SHIPMENT (TASK 2)</strong></td>
<td>Design, fabricate and deliver to the CDIF a prototypical coal-fired combustor for the integrated topping cycle power train. 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.</td>
</tr>
<tr>
<td><strong>PROTOTYPICAL 50 MW&lt;sub&gt;t&lt;/sub&gt; CHANNEL (TASK 3)</strong></td>
<td>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. 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.</td>
</tr>
<tr>
<td><strong>DIFFUSER (TASK 4)</strong></td>
<td>Design, fabricate and deliver to the CDIF a diffuser section for the integrated topping cycle power train.</td>
</tr>
<tr>
<td><strong>POWER CONDITIONING AND INVERTER (TASK 5)</strong></td>
<td>Design, fabricate and deliver to the CDIF current consolidation circuits for the prototypical channel.</td>
</tr>
<tr>
<td><strong>TEST ENGINEERING ACTIVITIES AT THE CDIF (TASK 6)</strong></td>
<td>Provide to CDIF personnel technical direction and guidance for the installation, checkout and testing of CDIF MHD power train components and appropriate auxiliary equipment.</td>
</tr>
<tr>
<td><strong>HARDWARE REPAIR/REPLACEMENT (TASK 7)</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>CHARTER AND PARTICIPATE IN AN MHD TECHNOLOGY TRANSFER, INTEGRATION AND REVIEW COMMITTEE (TASK 8)</strong></td>
<td>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. Review and integrate POC program schedules and integration issues and provide for technology transfer to potential future users.</td>
</tr>
<tr>
<td><strong>QUALITY ASSURANCE (TASK 9)</strong></td>
<td>Prepare and implement a plan to assure that prototypical power train components are manufactured per the approved design.</td>
</tr>
<tr>
<td><strong>INTEGRATED PROJECT MANAGEMENT (TASK 10)</strong></td>
<td>Provide for overall technical, programmatic and subcontract management for the project.</td>
</tr>
</tbody>
</table>
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 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 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

The component developers and MSE were sent copies of the revised Interface Document late last quarter. Their comments on the Interface Document were received this quarter and incorporated into the latest revision. This document was released as an Appendix to the Facility Impact Report.

This update required extensive changes to the process flow diagram, the cooling water diagrams, and the instrumentation diagrams due to the programmatic decision to remove the high pressure cooling system (HPCS) and replace it with a low pressure cooling system (LPCS).

3.1.2 Test Plan

The major effort on the Test Plan during this quarter was to hold a review at MSE to discuss the Test Plan, its contents, and the schedule for completion. It was decided that the basic format, i.e., the inclusion of the hardware description, the facility description, and the interfaces, would be kept. The plan should include all of the tests that the component developers would like to be run versus just the tests that there appeared to be time to conduct. This would provide MSE with the maximum requirements for testing.

The goal is to provide a completed, and approved, Test Plan prior to the first prototypical hardware delivery. This test plan will not cover the September testing but will concern itself with the testing that will commence with the installation of the Combustion Subsystem and the LPCS.

3.1.3 Facility Impact Report

The Facility Impact Report update was completed this quarter and the document was released in mid-February. This release completed the last of the Combustion Subsystem action items.

The main areas of update occurred in the following areas:

- Removal of the HPCS for combustion subsystem cooling and its replacement by the LPCS
- Decision to place the Current Consolidation cabinets in a new building adjacent to Building 50
- The updating of all of the process flow, cooling water flow, and instrumentation diagrams
- Updating of the prototypical hardware delivery schedule and the test schedule through completion of the duration testing
- An evaluation of the impact of the two reference operating conditions on the CDIF capability to deliver the required consumable flows
3.1.4 Channel Requirements Document

At the Denver coordination meeting held during this quarter, it was decided to publish a new document titled the "Channel Requirements Document" which would pull together, in one document, all of the requirements that the Channel Subsystem would place on the CDIF. Work on this document began in early April and continued through the end of the quarter.

When completed, this document will contain 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 will specify the nozzle and diffuser electrical layout and identify the maximum requirements for bleed resistors in these areas. The document will also clearly specify the instrumentation and metering that will be required for the Channel Subsystem.

It is planned that this document will be released for review early next quarter after which a joint meeting will be held to discuss the contents for completeness and impact on the CDIF. This meeting will be held near the end of May.

3.1.5 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.

The basic conclusion reached is that the delivery schedules for the POC hardware do support the facility modification schedule but there is very little time available for testing. Because of the facility modifications to the CDIF, and the lead times to perform the design and installation of the modifications, the test time is very limited. The chances for completing the component developers requested checkout tests and DVT's in time to start the duration testing in October of 1992 are very small.

The schedule issue will continue to be addressed in the coming months to ensure that slips in these dates do not further impact the baseline scheduled start of the duration testing.

3.1.6 Contractors’ Review Meeting

The annual Contractors’ Review Meeting was held on February 19th through the 21st. The Program Manager gave a summary of the past year’s progress.
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 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:
- An inspection of SA-387 steel components tested at the CDIF has been performed, a series of materials acid corrosion tests has been performed, and low temperature/pressure cooling water parameters were finalized.
- Design modification of the combustion subsystem internal components are being initiated to protect the components from low temperature corrosion.
- Water-side cooling panel corrosion protection was under development.
- Manufacturing development activities including the design of assembly fixtures were continued.

4.1.1 Low Temperature Corrosion and Cooling Water Parameters

As was reported in the 14th Quarterly Technical Report, the following activities were initiated to assess the impact of low temperature corrosion and to select proper cooling water parameters for the slagging stage and precombustor:
- Assessment of potential \( \text{H}_2\text{SO}_4 \) and \( \text{HNO}_3 \) concentrations in the precombustor and slagging stage. (Completed and reported earlier.)
- Survey of low temperature corrosion data in the pulverized coal burners and coal gasifiers and relevant industrial recommendations. (Completed and reported earlier.)
• Assessment of low temperature corrosion of the spool section tested during 250 hours at UTSI. (Completed and reported earlier.)

• Workhorse combustor low temperature corrosion data. (Reported herein.)

• Assessment of low alloy steel (SA-387) and silicone rubber (RTV 31) susceptibility to low concentrations of H₂SO₄ and HNO₃ at the 100°F to 200°F range. (Reported herein.)

• Assessment of different potential corrosion protection coatings (in progress).

4.1.1.1 Workhorse Combustor Low Temperature Corrosion Data

An inspection of the slagging stage air inlet filler installed in the workhorse combustor during the 14th quarter has been performed. The "filler" is the component which transitions from the precombustor to the slagging stage of the combustor. The top and bottom plates of the filler (Figure 4-1) were constructed from SA-387 (the same material as the prototypical cooling panels). It is cooled with 90°F water. The air inlet filler has an installation gap of ±0.15 inch with the pressure containing shell which in its turn is also water cooled. The combustion products might condense and accumulate on the filler outer walls. The filler was subjected to 91 hours of hot-fire testing and had more than 4000 hours of downtime. The post-test observations are shown in Figures 4-2 and 4-3. Substantial corrosion damage of the cold low-alloy sides is evident. The corrosion pits are 40 to 60 mils deep on the filler bottom plate and 20 to 30 mils deep on the top plate. Upon examination, by Ron Glovan (MSE), the pitting was found to be typical of acid attack. Samples of refractory material from the sidewalls of the filler and corrosion product from the top and bottom surface were analyzed for pH. The pH was 2.6 to 3.2 for all filler samples, confirming the presence of acidic material in post-test conditions. Samples of alumina/silica cloth material were also placed in various locations between component gaps in the combustor slagging stage. They were removed after

![Figure 4-1. Air Inlet Filler](image-url)
Figure 4-2. Top Plate Corrosion (91 Hours Firing Time, 4000 Hours Downtime)
Figure 4-3. Bottom Plate Corrosion (91 Hours Firing Time, 4000 Hours Downtime)
29 thermal hours and also analyzed for pH. The samples located in the assembly gap between the first spool and air inlet section had a pH = 4.9, whereas the samples taken from the chamber spool slag dump section assembly gap had a pH = 9.6, indicating the absence of acidic materials in the slag dump section. The main conclusion from the observation is that low temperature corrosion is a serious concern for the components made of SA-387 which are located in the air inlet section. The second conclusion (consistent with combustion calculations) is that the acidity level changes along the slagging stage axial direction. It peaks in the air inlet section, becoming basic in the slag dump section. The presence of nitrate and sulfate in the alumina/silica cloth samples indicates that both nitric and sulfuric acids are present. In addition, based on the high rate of corrosion observed on the workhorse filler SA-387 plates during limited test operations, it appears downtime corrosion may play a significant role in the corrosion process.

4.1.1.2 Susceptibility of Prototypical Combustor Materials to Low Concentration Acid Attack

To assess the prototypical combustor materials sensitivity to low concentrations of nitric and sulfuric acids, the following corrosion tests have been performed. SA-387 steel, 304L, 316L, Inc 625, OFHC and silicone rubber RTV 31 (filler material for the cooling panel/pressure assembly gap) were tested for 100 hours at 100°F in 1% nitric acid and 0.5% sulfuric acid solutions. These concentrations represent the probable upper bound of acid concentrations in the combustor and are based on the results of analysis of refractory material which had been located in the filler section during workhorse testing at the CDIF (reported in the 14th Quarterly). In addition, SA-387 steel and RTV 31 were tested during 138 hours at 200°F in a 1% nitric and 0.5% sulfuric acid solution. A summary of the test results is given in Tables 4-1, 4-2 and 4-3. High corrosion rates in the SA.387 samples (corrosion rates exceeding 1.5 mils in 100 hours) were found at all conditions. These corrosion rates do confirm that the 4000 hours of downtime (not the 90 hours of hot-firing) is the leading cause of the observed filler plate corrosion. Substantial RTV 31 degradation was found at 200°F. This is consistent with literature data that the RTV 31 operational temperature in nitric acid solution shall not exceed 150°F.

4.1.1.3 Recommendations

Based on the past hardware observations and the corrosion test results, the following decisions were made:

1) The combustor steady state water cooling temperature shall be limited to 110°F to protect RTV 31.
2) The cooling panels edges and backsides shall have corrosion protection. (A detailed description of the design changes is given in Section 4.1.2.)
3) A 200°F cooling water dryout loop shall be used to minimize downtime corrosion.

<table>
<thead>
<tr>
<th>TABLE 4-1. 100°F CORROSION TEST DATA WITH SULFURIC ACID</th>
</tr>
</thead>
<tbody>
<tr>
<td>(100 Hours @ 100°F, 0.5% H₂SO₄)</td>
</tr>
<tr>
<td>Sample</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>SA387</td>
</tr>
<tr>
<td>304 SS</td>
</tr>
<tr>
<td>316L SS</td>
</tr>
<tr>
<td>Inconel 625</td>
</tr>
<tr>
<td>OFHC</td>
</tr>
<tr>
<td>RTV 31</td>
</tr>
</tbody>
</table>
TABLE 4-2. 100°F CORROSION TEST DATA WITH NITRIC ACID

(100 hours @ 100°F, 1% HNO₃)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial Weight, g</th>
<th>Final Weight, g</th>
<th>Weight Loss, g</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA387</td>
<td>12.9511</td>
<td>12.7421</td>
<td>0.2090</td>
<td>Surface black, flaky. ≥ 1.6 mils recession depth.</td>
</tr>
<tr>
<td>304 SS</td>
<td>2.9403</td>
<td>2.9403</td>
<td>0.0000</td>
<td>Appearance unchanged.</td>
</tr>
<tr>
<td>316L SS</td>
<td>12.7129</td>
<td>12.7128</td>
<td>0.0001</td>
<td>Appearance unchanged.</td>
</tr>
<tr>
<td>Inconel 625</td>
<td>6.9890</td>
<td>6.9890</td>
<td>0.0001</td>
<td>Appearance unchanged.</td>
</tr>
<tr>
<td>OFHC</td>
<td>13.4932</td>
<td>13.4778</td>
<td>0.0154</td>
<td>Slight stain on surface in contact with glass.</td>
</tr>
<tr>
<td>RTV 3</td>
<td>1.8183</td>
<td>1.8133</td>
<td>0.0050</td>
<td>Bubbles clinging to surface in acid solution. Appearance unchanged.</td>
</tr>
</tbody>
</table>

TABLE 4-3. 200°F CORROSION DATA

(138 hours @ 200°F, 0.5% H₂SO₄)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial Weight, g</th>
<th>Final Weight, g</th>
<th>Weight Loss, g</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA387</td>
<td>12.9842</td>
<td>12.6534</td>
<td>0.3308</td>
<td>Surface black, rusty, flaky. ≥ 2.6 mils recession depth.</td>
</tr>
<tr>
<td>RTV 3</td>
<td>1.7878</td>
<td>1.7713</td>
<td>0.0165</td>
<td>Bubbles clinging to surface in acid solution. Appearance unchanged.</td>
</tr>
</tbody>
</table>

(138 hours @ 200°F, 1% HNO₃)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial Weight, g</th>
<th>Final Weight, g</th>
<th>Weight Loss, g</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA387</td>
<td>13.0094</td>
<td>12.3777</td>
<td>0.6317</td>
<td>Surface black, rusty, flaky. Left black mark on flask.</td>
</tr>
<tr>
<td>RTV 3</td>
<td>1.7573</td>
<td>1.6783</td>
<td>0.0790</td>
<td>Bubbles clinging to surface in acid solution. Sample bowed toward smooth surface. Water trapped in pores. Otherwise, appearance unchanged.</td>
</tr>
</tbody>
</table>

The cooling panel edges will be protected by overlaying 20-mil thick layers of Inconel 625. The backside of the panels will be protected by RTV 31 bonded to the panel. To ensure RTV 31 bonding to the cooling panel backsides, they will be primed with GE SS-4004 Primer. In bench tests, SS-4004 was applied to low-alloy steel surfaces and RTV 31 was poured over them. The samples clearly showed that the RTV 31 cannot be removed from a primed surface without tearing, but can easily be removed from an unprimed surface. However, the primer is not very visible on steel surfaces and can be wiped off easily with ordinary solvents. In one further test, the primer was applied to a low-alloy steel surface and then covered (encapsulated) with a thin layer of one-part RTV 106, another high temperature Red RTV product. The RTV 31 was poured and was effectively bounded (not removable without tearing). The conclusion from these tests is that the SS-4004 Primer (with a protective layer of RTV 106) will assure good bonding and will simplify cooling panel installation.
Some other alternate options for the backside protection under consideration are: Teflon FEP coating, Union Carbide detonation gun coatings LW-15 and LA-2, and chromium plasma spray and sealer. A number of test coupons were manufactured. They will be mounted on the top/bottom sides of the filler and tested at the CDIF. A 200°F dryout will be provided to the bottom plate to assess the dryout impact on downtime corrosion.

A layout of the coupons attached to filler panels is shown in Figure 4-4. Basically, the filler modifications include installation of material corrosion coupons on the backside (i.e. not the hot gas-side) of a "new" filler section. The "new" filler section was an existing component constructed from Inconel 625. A gap exists between the filler top and bottom plates and the first stage air inlet. For each plate, 160-mil high rails have been welded to top and bottom panels to prevent coupon shear damage during installation of the filler into the air inlet.

A summary of the coupons attached to the filler assembly top and bottom panels is as follows (see Figure 4-4):

<table>
<thead>
<tr>
<th>Coupon Number</th>
<th>Parent Material</th>
<th>Coating Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top panel (Reference to Figure 4-4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>SA387 Grade 11</td>
<td>RTV 31 Bonded</td>
</tr>
<tr>
<td>2</td>
<td>SA387 Grade 11 w T/C</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>SA387 Grade 11</td>
<td>RTV 31</td>
</tr>
<tr>
<td>4</td>
<td>SA387 Grade 11</td>
<td>Inconel 625 weld overlay</td>
</tr>
<tr>
<td>5</td>
<td>SA387 Grade 11</td>
<td>Bare SA387</td>
</tr>
<tr>
<td>6</td>
<td>SA387 Grade 11</td>
<td>Teflon Rep</td>
</tr>
<tr>
<td>7</td>
<td>SA387 Grade 11</td>
<td>Detonation gun LW-15</td>
</tr>
<tr>
<td>8</td>
<td>SA387 Grade 11</td>
<td>Detonation gun LA-2</td>
</tr>
<tr>
<td>9</td>
<td>SA387 Grade 11</td>
<td>Bare SA387</td>
</tr>
<tr>
<td>Bottom panel (Reference to Figure 4-4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>SA387 Grade 11</td>
<td>RTV 31 Bonded</td>
</tr>
<tr>
<td>11</td>
<td>SA387 Grade 11 w T/C</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>SA387 Grade 11</td>
<td>RTV 31</td>
</tr>
<tr>
<td>13</td>
<td>SA387 Grade 11</td>
<td>Inconel 625 weld overlay</td>
</tr>
<tr>
<td>14</td>
<td>SA387 Grade 11</td>
<td>Bare SA387</td>
</tr>
<tr>
<td>15</td>
<td>SA387 Grade 11</td>
<td>Teflon Rep</td>
</tr>
<tr>
<td>16</td>
<td>SA387 Grade 11</td>
<td>Detonation gun LW-15</td>
</tr>
<tr>
<td>17</td>
<td>SA387 Grade 11</td>
<td>Detonation gun LA-2</td>
</tr>
<tr>
<td>18</td>
<td>SA387 Grade 11</td>
<td>Chromium plasma spray &amp; sealer</td>
</tr>
</tbody>
</table>

Following each test, the coupon filler will have higher temperature water connected to the bottom panel (200°F) in order to simulate the dryout operations of the LPCS. The top plate of the filler is connected to city water which is typically in the range of 50°F. Two type K thermocouples, one in the bottom plate and one in the top plate, are utilized to confirm the post-test temperatures of the coupons. The coupon filler will be removed following the May 1991 CDIF shutdown and each coupon will be reviewed for corrosion.

4.1.2 Design Modifications Caused by Low Temperature Cooling Water

The MHD-ITC prototypical combustor was designed to be compatible with 450°F, 1200 psi cooling water (boiler feed water). The cooling panels are constructed from low alloy steel plate, A-387, Grade 11 (1.25% Cr, 0.50% Mo steel), a material compatible with 450°F cooling water operation. However, since low temperature (110°F, 300 psi) cooling water will now be used for CDIF testing, a greater potential for corrosion exists on non-gas facing low alloy steel surfaces which will operate below dew points. A low temperature corrosion protection is being incorporated into the combustor design. The design has been modified in four areas:
• The edges of low alloy steel panels in the most acidic regions of the combustor are weld-overlayed with a 20-mil layer of Inconel 625. The only components not overlayed are the exit section panels and slagging stage baffle.
• Silicone rubber foam has been removed from the combustor assembly. Pourable silicone rubber completely fills the panel installation gaps.
• Precombustor components in low heat flux regions which had been designed with low alloy steel will be fabricated from 347 stainless steel.
• All external combustor manifolds and piping will be made of Schedule 10 304L piping instead of Schedule 80 as a cost reduction measure.

When 110°F cooling water is used, panel edge and back surface temperatures drop below 200°F and nitric and sulfuric acids can condense. Inconel 625 overlays are used to protect low alloy steel panel edges from acid condensation. The weld overlays are 20 mils thick; a typical overlayed panel is shown in Figure 4-5. These weld overlays are necessary in the most acidic regions of the prototypical combustor: the precombustor transition, slagging stage air inlet, and slag dump.

The combustor design has an installation gap between the panels and the shell to accommodate panel thermal deflection and thus reduce panel stresses. This gap was initially filled with a combination of silicone rubber foam material and pourable RTV 31 (Figure 4-6). The RTV 31 was utilized to prevent coal migration behind the panels. Silicon rubber foam material was used to prevent the RTV from creating loads on the panels since the RTV in the gap will expand 15 mils between room temperature and 450°F. The foam material is not necessary for low temperature operation, as has been demonstrated through testing. The back surfaces of the panels are better protected from acid condensation when the installation gap is completely filled with dense RTV 31, thus the foam material has been removed from the installation.

![Figure 4-5. Prototypical Cooling Panel](image-url)
Figure 4-6. Standard Panel Penetration

In the precombustor, the baffle and transition ring material has been changed from low alloy steel to 347 stainless steel. These components have extensive surface areas which may fall below acid condensation temperatures and are not practical to overlay. The locations of the baffle and transition ring in the precombustor are shown in Figure 4-7. Since these components are in low heat flux regions, stainless steel materials are acceptable and the design remains compatible with 1200 psi cooling water. All the above design changes related to the panels and precombustor were incorporated in the drawings.

4.1.3 Manufacturing Development Activities

The prototypical combustor manufacturing development activities were focused on:
- Finalizing the second stage brazing,
- Optimization of the welded joint weld preps and weld parameters,
- Designing the prototypical combustor assembly fixture.

4.1.3.1 Second Stage Brazing

The key second stage manufacturing issues were resolved during this period. A development program was completed to identify essential braze parameters such as stainless steel cladding material, braze alloy, fixtures and braze cycle for the gas-side erosion protection liners. The program test matrix is shown in Table 4-4. The testing consisted of both bench scale and hot-fire testing in order to evaluate the erosion/corrosion resistance of the various cladding materials and braze alloy as well as the overall braze quality. On the basis of these test results, 446 stainless steel liners (0.075-inch thick) were chosen because of higher thermal conductance and resistance to cracking. Choice of braze alloy was based on a superior resistance of BAu-4 (82% gold) to chemical corrosion, as compared to BAg-8 (72% silver) material. The furnace vacuum braze cycle was defined to minimize potential negative results such as braze alloy corrosion and frame distortion. A non-destructive ultrasonic C-scan procedure was developed to evaluate braze
Figure 4-7. 347 Stainless Steel Hardware in Precombustor

<table>
<thead>
<tr>
<th>Table 4-4. Braze Development Test Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Braze Alloy</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>BAg-8</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>NICORO 80</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>BAu-4</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

X = tested

Notes:
1. 330SS is susceptible to stress-corrosion cracking in 2nd stage environment
2. Segmented liners related to OFHC stress-corrosion cracking
3. Non-uniform loading of grooved liner during braze results in braze voids
4. BAg-8 is susceptible to chemical pitting. Alloy to be used for repair work only
5. NICORO 80 rejected for excessive braze voids and OFHC erosion
6. Braze cycle defined to prevent OFHC erosion, porosity within braze joint and frame distortion
7. 446SS ungrooved, long liner configuration chosen using BAu-4 braze alloy (4 mil) based on CDIF operational experience and braze coupon analyses.
quality prior to final acceptance. The C-scan is capable of detecting voids as small as 0.063-inch in diameter within the braze interface, whereas a permissible void diameter, based on empirical data and heat transfer calculations, is 0.125 inch.

4.1.3.2 Welding Parameter Optimization

The effort to qualify a weld procedure and optimize weld preps continued during this period. The process was based on test samples designed to reflect typical weld configurations for the thermal panels, baffle, pressure shells and panel/shell installation. Table 4-5 presents the matrix for these tests and a summary of the test results. In particular, several different geometries were evaluated to identify optimal weld designs for SA 387, 304L and 347 stainless steel materials, including plug/panel, tube/panel, collar/panel and cover plate/panel joints. Other essential parameters such as weld filler material and pre-weld and post-weld heat treatment requirements were identical to those specified for actual hardware. Evaluation criteria consisted of a coupon proof test, dye penetrant inspection, and destructive cross-section and polishing to identify penetration and heat affected zones. As an example, the initial and final weld geometries for the cooling panel plugs are shown in Figure 4-8.

The results of these ongoing test samples are being incorporated into prototypical hardware design. Vendor selection requires each welder to produce acceptable weld coupons, per the TRW manufacturing requirements document, prior to award of the purchase order.

4.1.3.3 Assembly Fixture Design

The slag dump section and air inlet section assembly fixtures have been designed. They are shown in Figures 4-9 and 4-10. The fixtures will be used to dry-fit the cooling panels, weld them in-place, and to pour RTV 31 into the cooling panel/pressure shell assembly gap. As designed, the fixtures provide horizontal access to all final panel assembly welds. The air inlet fixture will be also used for the exit section assembly. A separate support stand will be designed to make a final assembly of the prototypical combustor prior to shipping to the CDIF.

4.1.4 Corrosion Protection During Combustor Manufacturing

Due to the extensive use of low alloy steel cooling panels in the prototypical combustor, water-side corrosion is of concern. If allowed to form, such corrosion can cause increased local metal temperatures, and in the extreme, possible failure of the panel. In addition, corrosion products introduced into the closed loop low pressure cooling system (LPCS) will cause an increased load on the purification equipment and possibly increase water conductivity. For these reasons, care must be taken to avoid corrosion of the cooling water passages, and if corrosion does form, procedures should be followed to ensure its removal.

This section provides an outline of the corrosion protection procedures which will be used following manufacturing and prior to shipping to the CDIF.

4.1.4.1 Post-Manufacturing Protection

To limit corrosion (rust) formation, water contact with the panel cooling passages will be minimized or eliminated during the vendor manufacturing phase. The approach will be to perform pneumatic leak checks at the vendor’s facility, with a hydrostatic proof test performed at TRW shortly after the panels are received. However, official receipt of the panels will still be contingent on passing this final proof test.

Flow testing of the panels will be done immediately following the proof test, on the same day if practical. The panels will be staged so that proof/flow tests are done in groups of 3 to 5 panels.

Following the flow tests, a two-step corrosion protection procedure will be followed. The first step is known as a preclean/prefilm procedure. This process will remove any dirt, grease or corrosion left over from the manufacturing process and will establish a passivating film which protects the panels for at least 30 days. The process will be performed using a small (5 GPM) flow cart, as shown schematically in Figure 4-11. The solution is mixed from concentrated chemicals in the holding tank, and is circulated at about 3 ft/sec for 36 hours at ambient temperature, then drained and flushed with water, followed by a
## Table 4-5. Weld Qualification Test Matrix

<table>
<thead>
<tr>
<th>Weld Joint</th>
<th>45 deg</th>
<th>50 deg</th>
<th>60 deg</th>
<th>65 deg</th>
<th>J-Groove</th>
<th>45 deg</th>
<th>50 deg</th>
<th>60 deg</th>
<th>65 deg</th>
<th>J-Groove</th>
<th>304L SS Material (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thermal Panel/Baffle Combustion Can Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Plug/Panel</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X (5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X (5)</td>
<td></td>
</tr>
<tr>
<td>• Coverplate/Baffle (6)</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>• Tube/Panel (7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>• Collar/Panel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X (8)</td>
<td></td>
</tr>
<tr>
<td>2. Shell Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Collar/Shell Penetration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X (9)</td>
</tr>
</tbody>
</table>

X = Tested

Notes
1. Unless otherwise stated, all welding performed with gas tungsten arc welding process (GTAW)
2. Inconel 625, ERNiCrMo-3, 0.002% sulfur max filler wire
3. ER347 SS filler wire (Precombustor baffle and transition ring)
4. ER309 SS filler wire
5. J-Groove Plug/Panel weld prep provides superior penetration
6. Coupon evaluation on-going
7. Weld penetration acceptance without weld prep
8. J-Groove penetration is acceptable. Possible cracking problems require interpass grinding of root pass
9. Shell/collar welding performed using GTAW and arc welding processes (pressure shells)
Figure 4-8. Initial and Final Plug Weld Geometry

Figure 4-9. Slag Dump Section Assembly Fixture
Figure 4-10. Air Inlet Exit Section Assembly Fixture

Figure 4-11. Schematic of Flow Cart for Panel Corrosion Protection
purge of GN2. The flow cart is designed so that at least 5 panels in series can be processed at the same time.

The second step is a long term storage corrosion protection procedure. The same flow cart (Figure 4-11) will be used to circulate a 0.5% solution of water-displacing rust-inhibiting lubricant for 24 hours. The panels will then be drained, purged with GN2, and placed in storage until integration into the spools. For an extra measure of protection, the panels will be kept under a GN2 blanket during storage. Although these procedures are fairly standard, some small low alloy steel coupons have been fabricated to assess how fast and under what conditions rust will form. The coupons will provide valuable qualitative data which will be hard to obtain once all the cooling circuits have been closed.

4.1.4.2 Post-Integration Protection

Following installation of the panels into the spool sections, integrated proof/flow tests will be performed on each major circuit (e.g. headend, air inlet, slag dump, etc.). These tests will establish required orifice sizes for flow balancing of the panels. Because the integrated flow tests will be run at design flow velocities, the protective film may be stripped from the cooling passages. Therefore, prior to shipping, the two-step corrosion protection process outlined above will be repeated for each of the major circuits. This step will be performed using a second, larger (35 GPM) flow cart. This second flow cart will be of nearly the same configuration as the first (Figure 4-11), and will be delivered with the hardware for use at the CDIF.

After the above procedure is completed, the circuits will be drained, purged with GN2 and capped for delivery to the CDIF.

Prior to placing the combustor in service, the protective film must be removed. Basically, this is done by repeating the preclean/prefilm step for each of the circuits using the larger flow cart. Detailed procedures are presently in development for the corrosion protection methods outlined above.

4.1.5 Coal Injector Wear Ring Testing

The replaceable coal injector wear ring made of 446 stainless steel was removed and inspected after 91 coal flow hours. The wear ring removal was quick and easy without galled threads, burned O-rings or coal packing behind the wear ring. This was achieved by incorporating the following design changes:

a) By replacing fine threads with coarse ones treated with high temperature lubricant, and
b) By providing a redundant O-ring behind the wear ring.

Erosion inspection indicated a 0.61% material weight loss with a maximum geometry change of 15 mils. These weight loss and geometry change values are much less than previously observed for the 310 stainless steel wear ring. Based on the workhorse hardware inspection and wear ring data for the atmospheric combustor (where a number of other materials such as stellites and a high strength steel were tested), 446 stainless steel is the best wear ring material. The wear ring is fully reusable and will be reinstalled in the combustor to accumulate more wear data and to assess a required replacement time.

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

During this time period most of the raw materials were procured and shipped to the component manufacturing vendors currently identified. The balance of the raw materials have been ordered and will be delivered to the remaining vendors during the month of May.

The vendor shop planning document for the second stage was approved and the manufacturing process begun.
The development of the vendor manufacturing planning for the combustor cooling panels continued and weld coupons were received for evaluation.

Revised quotations for the pressure shell components were received and evaluated. A purchase order for these components was placed with March MetalFab, Inc. during April. The first review of the vendor shop planning was initiated. Additionally, vendor recommended changes to the welding specification for ease of manufacturing is currently being reviewed by TRW.

Revised vendor quotations have also been received for the combustion can, slagging stage baffle and endplates. Purchase orders for all have been awarded and the manufacturing shop planning and review process initiated. Applicable weld coupons have been received from the vendor and are currently being reviewed by TRW.

As the result of design changes related to operation with 110°F cooling water, a request for revised vendor quotations was necessitated for the cooling panels and the precombustor baffle and transition ring because it will affect the manufacturing process.

Procurement of assembly hardware such as seals, nuts, bolts, valves, etc., continued.

4.2.2 Low Pressure Cooling Subsystem Procurement

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

- Two bids were received for the design, manufacturing, test and delivery of the LPCS.
- Based on technical competition, Ellis & Watts of Batavia, OH was selected as the most capable vendor.
- The LPCS equipment specification was modified to lower the system operation temperature from 210°F to 110°F. Ellis & Watts prepared a modified bid to reflect this and other minor changes.
- Negotiations with Ellis & Watts were completed in early April, and LPCS manufacturing planning activities were initiated.

As described in the 14th quarterly report, the primary cooling water (PCW) working group recommended the procurement of a dedicated low pressure (300 psi) cooling skid for cooling the POC combustion subsystem hardware. Based on this recommendation, TRW prepared an equipment specification and RFP for the LPCS. The LPCS will provide cooling water for the slagging stage and precombustor, with the second stage cooled by the CDIF PCW system (as is presently the case for the workhorse hardware).

Proposals for the LPCS were received in mid-February from Ellis & Watts of Batavia, OH and ACL Technologies of Santa Ana, CA. Based on a technical evaluation of the proposals, Ellis & Watts was selected as the most capable vendor. This decision was based on their superior understanding of the technical requirements and their specific experience in the production of skid-mounted cooling systems.

Due to concerns about acid condensation in the combustor, the LPCS supply temperature was originally specified as 210°F. However, as described in Section 4.1.1, a decision was made to reduce the supply temperature to 110°F and to provide acid protection using Inconel weld overlays on the panel edges. The LPCS will retain the capability of providing a post-test trickle flow (150 GPM) to dry the combustor out at up to 200°F. Based on this change, the equipment specification was modified and sent to Ellis & Watts for a re-bid. A summary of the basic LPCS operating parameters is shown in Table 4-6.

Negotiations with Ellis & Watts were completed in early April, and final preparations of the subcontract package are underway. Ellis & Watts have initiated manufacturing planning activities, and the subcontract will be in place by early May.

The overall schedule for the LPCS procurement is shown in Table 4-7. An informal Conceptual Design Review is scheduled for 29 May 1991, with the Final Design Review on 26 June 1991. Both reviews will be held at the Ellis & Watts plant and will be attended by both TRW and MSE personnel, as appropriate. Delivery of the LPCS to the CDIF is scheduled for 15 December 1991.

4-17
### TABLE 4-6. LOW PRESSURE COOLING SYSTEM OPERATING PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Normal Operating Mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Flow Rate (lb/sec)</td>
<td>173</td>
<td>N/R</td>
<td>208</td>
<td>±10</td>
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<td>±10</td>
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<td>±10</td>
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<tr>
<td>Supply/Return (\Delta T) (°F)</td>
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<td>9</td>
<td>27</td>
<td>N/A²</td>
</tr>
<tr>
<td>Heat Rejection (MMBtu/hr)</td>
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<td>5.7</td>
<td>17.8</td>
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</tr>
<tr>
<td>Water Resistivity (4) (Mohm-cm)</td>
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<td>0.5</td>
<td>N/R</td>
<td>N/R</td>
</tr>
<tr>
<td>Water pH</td>
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<td>N/R</td>
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<tr>
<td>Water Dissolved (O_2) (ppm)</td>
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<td>N/R</td>
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<td>B. Heat-Up Mode</td>
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<tr>
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<tr>
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<td>±0.2</td>
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<tr>
<td>System Cool-Down Rate (°F/min)</td>
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<td>Water Resistivity (4) (Mohm-cm)</td>
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<td>N/R</td>
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<tr>
<td>Water pH</td>
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<td>±0.5</td>
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<tr>
<td>Water Dissolved (O_2) (ppm)</td>
<td>2.0</td>
<td>N/R</td>
<td>N/R</td>
<td>±1.0</td>
</tr>
</tbody>
</table>

### Notes:
1. Measured at the connecting flanges of LPCS skid.
2. N/A: Not applicable.
3. N/R: No requirement.
4. Measured at the supply flange from the skid.

### TABLE 4-7. LOW PRESSURE COOLING SYSTEM (LPCS) PROCUREMENT SCHEDULE

<table>
<thead>
<tr>
<th></th>
<th>1991</th>
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<td>1/2/3/4</td>
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<tr>
<td></td>
<td>JUN</td>
<td>JUL</td>
</tr>
<tr>
<td></td>
<td>1/2/3/4</td>
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</tr>
<tr>
<td>SUBCONTRACT START</td>
<td>Δ</td>
<td>Δ</td>
</tr>
<tr>
<td>CONCEPT REVIEW</td>
<td>Δ</td>
<td>Δ</td>
</tr>
<tr>
<td>FINAL DESIGN REVIEW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PROCUREMENT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• LONG LEAD ITEMS</td>
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<td></td>
</tr>
<tr>
<td>MANUFACTURING</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• FABRICATION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• MECHANICAL ASSEMBLY</td>
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<td></td>
</tr>
<tr>
<td>• ELECTRICAL ASSEMBLY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• TEST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHIP LPCS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INSTALLATION</td>
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<tr>
<td>ACCEPTANCE TESTS</td>
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</tbody>
</table>
5. PROTOTYPICAL CHANNEL DESIGN (TASK 3)

During this reporting period, work has been conducted to finalize the channel design. A summary of the channel design and fabrication is presented in Section 5.1. The results of the 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 potential problem areas in the channel design including: 1) leaky water tubes, 2) pitting on sidewall coupons, and 3) water-side corrosion. Some of the water tube elements that were installed in the 1A1 workhorse channel leaked. The problem was attributed to incompatible braze and tube materials, and was rectified as described in Section 5.3. Pitting of prototypical sidewall coupons was observed in the CDIF workhorse testing. The cause and solution for this problem are described in Section 5.4. The status of water-side corrosion tests for prototypical elements is outlined in Section 5.5. This includes the latest results of tungsten-copper elements at controlled pH, heat flux and voltage levels. The status of channel fabrication is detailed in Section 5.6.

5.1 1A4 CHANNEL DESIGN AND FABRICATION

5.1.1 Summary

The final design of an MHD channel for the Integrated Topping Cycle Program proof-of-concept 1000-hour test is complete. The channel, designated as the 1A4, is a linear, supersonic, diagonally loaded generator. It has a segmented diagonal-bar sidewall construction. The essential design elements are summarized along with the an overview of the fabrication methodology in this section. The 1A4 channel is designed to be capable of 1.5 MWe power output and a lifetime of 2000 hours.

Acceptance of MHD as a viable technology by the utility industry is contingent upon demonstration that MHD channels can be operated for extended durations. Thus, to achieve this requirement, design emphasis was placed upon durability and reliability. Because damage to the channel by electrical arcs represents the most critical channel lifetime issue, special emphasis was placed on measures to mitigate this problem. Gas-side corrosion ranks as the second most difficult challenge. This issue was addressed by selection of materials to provide the best wear characteristics and by designing gas-side elements to minimize the electrical stresses that accelerate the material wear rates.

Anode gas-side performance relies primarily on platinum caps to minimize wear due to electrical arcs and electrochemical corrosion. Backup to the platinum capping is provided by tungsten. Aluminum nitride ceramic caps are brazed onto the electrodes to electrically insulate the corner joint. Tungsten is the primary gas-side protection on the cathode wall and in the high electrochemical stress regions on the sidewalls. Gas-side protection on the remaining sidewall elements is furnished by using tungsten-copper.

Because of its superior resistance to electrochemical corrosion, tungsten was chosen as a gas-side material in areas with high electrical stresses. Although it is well suited for use in the MHD gas-side environment, special consideration was given to fabricating the material and machining it to the final shape. Cross-rolling to improve material ductility, in-process quality inspections to ensure material integrity, and proper orientation of the material lamination on the finished elements are among those considerations.

A unique aspect of the design is the extensive application of capping to protect water-cooled base materials. Successful protection of base materials by platinum and tungsten caps depends on the integrity of the braze joints. Excessive voids at the cap-to-base braze interfaces will result in reduced heat conduction to the water-cooled bases, raising the cap temperatures which will result in accelerated corrosion. Comprehensive braze development and braze void analyses were successfully undertaken to minimize braze defects and to check the integrity of braze interfaces for both the metal-to-metal and the ceramic-to-metal brazes.

Results from design confirmation tests conducted in the Avco/TDS Mark VII and 1A1 channels were used to confirm design choices and verify 1A4 channel component fabrication techniques. Pertinent findings from these studies, and from engineering development activities undertaken to evaluate channel
components and fabrication techniques, were incorporated in the design and are utilized in fabricating the 1A4 channel.

5.1.2 Introduction

Research and test activities required for the design of the Integrated Topping Cycle (ITC) program MHD channel have been completed and fabrication of the channel is underway. The 1A4 channel was designed with the ability to produce 1.5 MW_e and to have a minimum gas-side lifetime of 2000 hours and 500 cycles.

Performance design requirements were achieved analytically and verified by comparison to the measured performance of a similarly designed channel, the 1A1. Achieving the required performance entailed matching an aerodynamic loft and electrical load for the coal combustor plasma conductivity and pressure. As previously reported, this objective was exceeded (Reference 5-1).

The channel lifetime requirement was the more difficult objective of the two to obtain and even more difficult to verify. Channel durability and reliability requirements were addressed using test results and engineering data from several sources. Tests performed using the Mark VI, Mark VII and 1A1 channels, in conjunction with bench-scale tests, published engineering data and calculations, were collectively used to meet the design requirements. However, confirmation that the 1A4 channel design meets the lifetime goal can only be established during the 1000-hour proof-of-concept (POC) testing.

Details of the design requirements and philosophy have been previously covered (Reference 5-1). The intent of this section is to describe the final aspects of the 1A4 channel design and fabrication processes. Fabrication activities are emphasized because of the severe mechanical, thermal and electrical stresses that are imposed upon the MHD channel during operation. Reliable operation of the 1A4 channel for 1000 hours in this severe environment requires that all components be built to specification. Hence, an added degree of rigor and attention to detail must be imposed during fabrication.

This discussion is organized to provide an overview of the 1A4 channel design followed by a description of the anode, cathode and sidewalls. Design details describing the gas-side element materials and structure are summarized. Cooling, wiring and interface requirements are provided in subsequent sections. 1A4 channel fabrication discussions include an outline of various pre-fabrication qualification and in-fabrication steps undertaken as value-added measures to ensure that the final product achieves the goals established by the design.

5.1.3 1A4 Channel Design

The 1A4 channel is designed with durability and reliability as primary objectives. Because the occurrence of severe electrical faults will shorten channel life more dramatically than any other cause, much of the design emphasis is placed on measures that will prevent or mitigate them. Briefly stated, these measures include the use of interelectrode arc gaps, the incorporation of corner joint ceramic, the use of non-arc tracking wall liners, and the utilization of plastic water manifolds. External current control circuits are also provided to buffer cathode wall voltage nonuniformities from being reflected onto the anode wall.

MHD channel gas-side surfaces are subjected to a very harsh environment and the wear mechanisms encountered are as aggressive as found in any system. The coal-fired MHD channel gas-side surfaces are subjected to high temperature electrochemical corrosion, electrical arc erosion, and particle erosion wear mechanisms. Materials relied upon for the 1A4 channel design, that are sufficiently resistive to the 1A4 channel wastage processes, include tungsten, platinum and a tungsten-copper composite. These materials are used exclusively to prolong life of MHD channel gas-side surfaces. Amplification of these design features, as well as other salient features of the channel design, are presented in subsequent sections.

An overview of the 1A4 channel, nozzle and diffuser as they sit in the magnet bore is presented in Figure 5-1. The 1A4 channel, which is integral with the nozzle, is 15.7 feet long and has a rectangular, linearly divergent cross-section comprised of four separable walls. Two views of the channel are provided.
in Figure 5-2. The top figure is a cross-section of the 1A4 channel taken through the sidewalls, along the entire length. The bottom figure shows a side view of the 1A4 channel mounted on a strongback, which is used for channel assembly and transport. The gas-side, water-cooled electrode and sidewall elements are attached to a 1-inch thick, epoxy bonded fiberglass laminate (NEMA G-11), which serves as a structural member. As shown in Figure 5-3, there is a liner of NEMA Grade G-7 fiberglass laminate plastic between the gas-side elements and the G-11 wall.

The G-7 laminate is used to prevent permanent, catastrophic damage to the G-11 channel structure in the event interelement arcs impinge on the back wall. The binder in the G-7 plastic is silicon, which remains resistive when charred. Thus, arc impingement on the liner does not produce a conductive char, and hence the G-7 provides protection against permanent interelement faults at the channel back-wall and prevents damage to the G-11 structural member. The walls are bolted together and mating surfaces are sealed with an adhesive silicon rubber as depicted in Figure 5-4.

5.1.3.1 Nozzle

The 1A4 channel and nozzle are integrally constructed. The inlet to the convergent section of the nozzle bolts directly to the combustor second stage outlet. The convergent-divergent nozzle is 1.5 feet long. The nozzle top and bottom wall elements are segmented axially at the electrode wall pitch. The nozzle sidewall elements are also transversely segmented which reduces the erosive effects of circulating electrical currents on the nozzle sidewall. The gas-side surface is comprised of tungsten caps that are brazed onto water-cooled copper bases.

Figure 5-1. 1A4 Channel, Nozzle and Diffuser in Magnet Bore
Figure 5-2. 1A4 Channel Top View, Cross-Section and Side View on Strongback

Figure 5-3. Cross-Section of 1A4 Channel Showing Materials of Construction, Wiring, Hosing, Manifolding and Fit in the Magnet Bore
The anode sees the most severe electrical service and has a three piece platinum cap to provide primary protection of gas-side surface. As shown in Figure 5-5 the platinum caps are brazed onto tungsten caps, which provide a second level of protection for the water-cooled copper bases.

Electrical arc impingement on the platinum surface provides the thermal conditions for grain boundary attack. The extent of this attack is proportional to the size of the platinum grains, i.e., smaller grain size platinum is affected least. Platinum can have a reduced grain size established at time of manufacture by the addition of minute amounts of zirconia. The doped platinum, known as zirconia grain stabilized (ZGS), has been tested in both the Mark VII and 1A1 channels. The smaller grains have been proven in reducing the effects of arc impingement on the platinum gas-side surface (Reference 5-2).

A tungsten top cap provides backup for the platinum caps in the event a platinum cap is lost or violated. The tungsten is fabricated from a press-sintered material that is rolled at elevated temperature into the wrought form. During the rolling process, a laminar grain structure is developed, leaving the tungsten with asymmetric mechanical properties. Improper orientation of the cap laminations when it is attached to the base element can result in cracking of the material along the laminations. These mechanical stresses are induced at the mating surface when two dissimilar metals are brazed. Depending upon their orientation, these cracks can result in loss of a heat transfer path from the gas-side surface to the water-cooled boat or in a catastrophic failure (loss) of the cap. However, orientating the laminations parallel to the heat flux eliminates this problem (see Figure 5-6). In this orientation, cracking of the cap material neither diminishes the mechanical integrity of the cap attachment nor impedes heat transfer.

Arc stretching gaps at the anode base are provided to quench interanode arcs. Grooves in the anode, similar to the ones depicted in Figure 5-7, have been proven effective in reducing the number and dwell time of spurious interanode arcs impinging upon the back-wall (Reference 5-1). However, in the event that
Figure 5-5. 1A4 Anode Bars

Figure 5-6. Orientation in Tungsten Cap Laminations for Anodes
arcs are driven into the back-wall, a liner of 0.375-inch thick G-7, introduced earlier, provides protection for the G-11 wall structure.

An electrically weak (low resistance) insulator at the anode-to-sidewall corner joint can promote premature breakdown and accelerated failure of the anode. Brazed aluminum nitride ceramic caps are used to provide electrical isolation between the sidewall and anode wall at the corner joint. The aluminum nitride ceramic caps are vacuum brazed onto a tungsten cap. These ceramic insulating caps have proven effective in providing a sound anode-to-sidewall insulating joint in tests on the 1Al channel (Reference 5-2).

Satisfactory performance of the anode wall depends upon slag coverage on the gas-side surface. Therefore the anode was designed with grooves between adjacent anode caps, which are spaced and staggered as shown in Figure 5-8, providing footholds for slag attachment. In addition, as shown in Figure 5-5, recession of the interanode boron nitride insulators promotes slagging.

5.1.3.3 Cathode Wall

The 1A4 cathodes have water-cooled bases, capped with wrought tungsten elements. As in the case of the anode caps, proper orientation of the tungsten laminations is required to prevent the potential for loss of a cap or impedance to heat transfer if cracks develop at the lamination boundaries. The cathode is capped with an aluminum nitride ceramic at the corner joint intersection with the sidewall.

A typical cathode is shown in Figure 5-9. Spaces between adjacent caps on consecutive electrodes are staggered to encourage slagging and minimize the propensity for mechanical erosion in the direction of the flow. The cathode back-wall is designed with similar materials as the anode, but the G-7 plastic laminate is thinner, 0.187 inch. The thinner char resistant material provides suitable protection here. The intercathode
Figure 5-8. 1A4 Anode Wall Cap Segmentation and Layout

Figure 5-9. 1A4 Cathode Bars
arcs are driven toward the plasma away from the plastic. Hence, arc dwell time on the cathode back-wall is short, and thus less material is required to protect the cathode G-11 structural wall from arc impingement.

Boron nitride ceramic provides insulation between adjacent cathodes. Water tubes and water passage end plugs for both the cathodes and anodes are made from lead free naval brass and are torch brazed onto the copper bases.

5.1.3.4 Sidewall

The sidewall is of constant height from front to back. The channel divergence is provided entirely by the electrode walls. The sidewall elements are of a segmented Z-bar design. A layout of the sidewall is shown in Figure 5-10. The sidewall has three gas-side material cross-sections, which are depicted in Figure 5-11. The different cross-sections are located in three zones of the sidewall. In the first zone, the two rows adjacent to the cathode wall, the elements are tungsten-copper (75% tungsten-25% copper, press sintered composite) bases with brazed tungsten caps. A second zone of the sidewall has elements with copper bases and brazed tungsten caps, while full-height tungsten-copper bar elements comprise the third zone.

The tungsten capping along the bottom two rows of the sidewall protects the gas-side surfaces in the event that high voltage gaps occur on the cathode wall. High voltage, arcing gaps can be established on the cathode due to slag polarization. These high voltages reflect onto the sidewall, accelerating the electrochemical and arc erosion processes. Tungsten capping enhances the durability of these elements in the presence of high-voltage arcing gaps.

In tests conducted to date, the iron oxide injection onto the cathode wall has, to a large extent, mitigated high-voltage arcing gaps that are caused by cathode slag polarization. However, only limited testing with iron oxide slurry injection has been completed. The longest single test only lasted 12 hours. Hence, the

![Figure 5-10. 1A4 Channel Sidewall Gas-Side Material Zone Layout](image)
long term operational effects of iron addition to the slag are unknown. Therefore, the sidewall is designed to operate with high-voltage interelectrode gaps on the cathode wall in the event iron oxide cannot be used, or is not effective during the POC test series.

Interelement arcing below the cap level has been observed on sidewall elements adjacent to the cathode wall when high voltage intercathode gaps persist. Since tungsten-copper is far more resistant to erosion at arcing gaps than copper, it was chosen as a base element material in zone one of the sidewall.

The sidewall elements are 1.125 inches high. Interelement insulators are full height boron nitride ceramic. The tungsten caps are vacuum brazed onto the copper and tungsten-copper bases with a gold-nickel alloy. Lead free naval brass water tubes are torch brazed onto the bases. They have serrated ends for connection of water hoses.

5.1.3.5 Wiring

Nominal electrode currents will be 20 amperes at the design operation point, while interelectrode voltages are calculated to be 35 volts. Maximum electrode currents and interelectrode voltages are 40 amperes and 70 volts, respectively. To accommodate these requirements, a ten gauge stranded wire with teflon insulation rated to 10,000 volts dc is used. The upper current rating for the wire is 75 amperes dc. The upper design operating temperature for the wire is 392°F, which is below the wire temperature due to ambient conditions and joule heating during operation.

To ensure adequate wire-to-wire voltage separation, the wires will be routed via brackets to a connector panel mounted on the channel aft end. The brackets also serve to constrain the wires against movement due to Lorentz (jxB) forces.
5.1.3.6 Water Cooling

Manifolds and hoses used for cooling the electrode walls and sidewalls are schematically depicted in Figures 5-12 and 5-13, respectively. Water velocities through the elements vary from 30 ft/sec in the high heat flux region to 8 ft/sec in the aft, where the heat flux is lower. Hosing lengths are minimized by the use of transfer manifolds. All of the manifolds are designed using Acetal, a copolymer plastic. Plastic permits long axial manifolds and short connector hoses without the fear of arcing or electrochemical corrosion of water tubes. Similarly designed metallic manifolds would not provide this assurance. Connections to the manifolds will be made using a barbed hose fitting, threaded into the manifold body and sealed with an O-ring. Refrigeration hose, which has been proven through service in the Mark VI, Mark VII and 1A1 channels, will link the manifolds to the electrode elements. Sidewall elements will be interconnected along a "Z" with preformed jumper hoses.

5.1.3.7 Diffuser

The diffuser is designed in four sections: two constant area supersonic sections and two subsonic sections that diverge at a half angle of 2.5 degrees. The forward supersonic section has segmented elements to mitigate the effects of circulating currents in this region. The magnetic field at the diffuser entrance is approximately 0.7 tesla and the plasma flow is supersonic. These conditions result in sufficiently high Faraday voltages to induce circulating currents along the sidewalls if they conduct.

The supersonic diffuser section segments are constructed using a water-cooled base with a 0.125-inch thick, 446 stainless steel gas-side cap that is explosion bonded onto a 1-inch thick copper plate. The cap is grooved to promote slag retention. The segments are attached to a 1-inch thick G-10 fiberglass laminate. Boron nitride ceramic spacers are placed in 0.075-inch gaps between the segments. The segmented wall construction is shown in Figure 5-14.

Figure 5-12. 1A4 Electrode Wall Cooling Scheme
Figure 5-13. 1A4 Sidewall Cooling Scheme

Figure 5-14. Supersonic Diffuser, Segmented Section
The remaining three diffuser sections are comprised of four separable, 1-inch thick copper plates. The plates have gun drilled water cooling passages and are grooved to retain slag.

5.1.3.8 Packaging

Efficient packaging of hosing, wiring, and manifolds permit the 1A4 channel to fit handily in the magnet bore. Because transfer manifolds are used to provide water connections between many of the electrodes, a large number of hoses are eliminated. All manifolds, wires and connectors will be held in place with brackets, eliminating any possibility of interference with the magnet bore liner. The layout of these external components is accomplished using a full scale mock-up of the 1A4 channel.

5.1.3.9 Interfaces

The 1A4 channel will be installed at the Department of Energy's Component Development Test Facility (CDIF) in Butte, Montana in the same test bay that currently accommodates the 1A1 channel. One objective of the 1A4 channel design effort was to utilize existing interfaces at the CDIF. This was accomplished to the extent possible, and for the most part, interface requirements of the 1A4 channel were relaxed from those required for the 1A1 channel.

Mechanical interfaces occur: 1) at the inlet with the second stage, 2) at a midway location in the magnet bore with the support stand, 3) under the diffuser via a stand, and 4) at the outlet end of the diffuser with the facility quench duct (see Figure 5-1).

The 1A4 channel inlet is designed with a flange that will bolt to the second stage outlet. At this interface, the design operating pressure is six atmospheres. The flange is designed to accommodate this pressure and the added mechanical forces due to weight and thrust. The 1A4 channel is supported near the center with a stand that fits through a slot in the magnet bore. This support scheme is similar to that used for the 1A1 and allows axial movement of the channel. The diffuser will rest on the same stand presently used by the existing diffuser. The final mechanical interface is between the last diffuser section and the quench duct. This interface is made using a slip joint that allows axial growth of the channel, while providing a low pressure gas seal. (Operating pressure at this location is only a few inches of water above atmospheric.) Axial growth will be about 0.5 inch.

Other interfaces with the facility include electrical connectors for the electrodes, cooling water connections, static pressure taps and purges, as well as sidewall voltage measurements.

The 1A4 channel has process flow interfaces for iron oxide slurry and nitrogen purges. Provisions for iron oxide injection are made for top and bottom wall iron injection ports in the convergent section of the nozzle. These injection ports will also require a purge gas connection. A schematic of the iron oxide slurry injection bar is shown in Figure 5-15.

5.1.4 Fabrication

Fabrication of the 1A4 channel required the completion of several pre-fabrication activities including: devising material specifications and evaluating fabrication methods and quality assurance measures that ensured that the final product complied with both the letter and intent of the design. These measures were necessary because of the requirement for operational reliability and because of the nature of some of the materials used. In addition, the large number of critical brazes, both gas-side capping and water-side cooling, that must be flawless led to the development of fabrication and nondestructive test techniques. These methods minimize any chance for the installation of defective components in the 1A4 channel.

5.1.4.1 Pre-Fabrication Activities

Three areas of particular concern were integrity of the: 1) wrought tungsten caps, 2) gas-side cap brazes, and 3) water tube and end plug brazes. Extensive pre-fabrication activities were undertaken to develop means to ensure that these potential problem areas were resolved prior to the onset of fabrication. The specific measures that were undertaken to address these issues included: 1) the development of a wrought tungsten material specification and post-machining inspection techniques, 2) the development of
an inspection technique to detect voids in the electrode and sidewall element cap brazes, and 3) a means to ensure sound attachment of water tubes and end plugs to the water-cooled base elements.

**Tungsten Material Specifications and Post-Machining Inspection**

Wrought tungsten was chosen as a primary gas-side material on the cathode and sidewalls and as a backup material under platinum on the anode because of its resistance to corrosion encountered in the coal-fired MHD environment. However, wrought tungsten has low tensile strength in a plane perpendicular to the laminations. Thus, relatively low mechanical forces applied in this plane can cause cracking of the material.

Wrought tungsten is hot-rolled from press-sintered tungsten billets. During this rolling process, work put into the material provides it with strength and ductility, but also produces the laminar structure that results in asymmetric strength properties (weakest in the lamination plane). In addition, as the tungsten billet is rolled during the fabrication process, cracks can be established in the parent material, especially along the plate edges.

Grain structure uniformity throughout the plate thickness was desirable for our application, thus a special rolling and heat treatment schedule was required. The tungsten plate is cross-rolled to widen the elongated grain structure produced during the rolling process. This measure reduces some of the structural asymmetry. In order to obtain sufficient working of the material, the tungsten stock had to be rolled down to one-half or less of the thickness of the press-sintered billet. Limitations at the tungsten mill established the maximum plate thickness, which was 0.7 inch.

To ensure crack free material, an ultrasound inspection of the plate was necessary to identify defective regions. These regions were removed and the sound regions of the plate were ground into bar stock. Because tungsten could crack if grinding speeds are too high, or if insufficient cooling was used, the

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**Figure 5-15. Iron Oxide Injection Slurry Bar**

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finished bar stock was zygloyg inspected for surface cracks. Machining tungsten into the final shapes was primarily accomplished by electric discharge machining (EDM). Although it was unlikely that this machining method imparted cracks, each finished cap was zygloyg inspected for surface cracks to ensure that they were defect free.

Because tungsten is notch sensitive, it was necessary to radius the inside corners that resulted from machining the slagging groove and the platinum corner cap slot. A radius of 0.030 inch was found to be satisfactory. This machining requirement was well suited to the EDM process.

Cap Brazing Inspections

The brazes used to attach the caps (platinum, tungsten and aluminum nitride) to their respective substrates provided good thermal contact for adequate cap cooling. This aspect of the fabrication is crucial, because if the brazes have a large void, overheating of the protective cap material can result in premature or catastrophic corrosion of the cap. Therefore, mechanically sound brazes alone are not sufficient, and testing to establish adequacy of the braze cannot be completed by a simple mechanical test or inspection of braze fillets.

A nondestructive ultrasonic test method was employed for identification of braze defects (voids or unwetted regions) at the cap-to-braze interface. This method, termed c-scan, uses back reflections from a high frequency signal to identify voids in a material. An unwetted surface (or void) at the braze interface shows up as a discontinuity. The size of the defect can be established by using a calibrated defect and tuning the detector to trigger on back reflections of a predetermined magnitude. For a given combination of materials and geometric configurations, the back reflection is proportional to the defect size. The allowable void sizes were established via heat transfer calculations for each type of brazed cap.

The c-scan ultrasonic inspection technique results in a hard copy map of bonded and unbonded areas from which the size of each braze defect can be determined. Inspection procedures were established to detect defects in tungsten-to-copper, tungsten-to-tungsten copper, platinum-to-tungsten and aluminum nitride-to-tungsten bonds. Thus, elements with excessive cap voids are identified and rejected.

Braze Qualifications

Prior to the onset of the channel manufacture, procedures for torch brazing water tubes and end plugs to the base elements were qualified, as were the brazing personnel. Qualifying both the braze technique and personnel was accomplished by completing brazes on test coupons to an established procedure, followed by visual inspections, hydrostatic tests and mechanical tests. The visual inspections included cross-sectioning braze joints and inspecting them for voids. Development of the procedures and acceptance criteria were based upon industrial standards (Reference 5-3).

5.1.4.2 Fabrication and Quality Assurance Measures

As in any manufacturing activity, a successful conclusion depends upon adherence to proven fabrications methods. In addition, the development of techniques to ensure that the product was fabricated in accordance with the specifications and procedures was important to improve confidence in the finished product. In this spirit, standard commercial practice was followed. Specifically:

- Materials specifications were called out on the drawings and certifications were obtained to verify that the materials met the specifications.
- Receiving inspections were made to ensure the dimensional correctness of the machined parts.
- Specific fabrication procedures were developed and qualified so that the 1A4 channel fabrication proceeded in a proven and uniform manner.
• Checklists and sign-off sheets accompanied parts and subassemblies, to guarantee compliance with the fabrication procedures. This was accompanied by independent Quality Assurance inspections during the fabrication process.

• Various in-process inspections and post-assembly tests were also used to verify product quality at all stages of fabrication. These measures included visual inspections, hydrostatic inspections, dimensional checks, pneumatic leak checks, electrical continuity checks, resistance checks and flow checks. A typical series of in-process inspections is depicted in a flow chart shown in Figure 5-16.

5.1.4.3 Testing

Throughout the early phases of the design process, and as fabrication methods were established, "typical" elements and 1A4-style components and subassemblies were tested in the Mark VII channel and in bench-scale tests. These tests included mechanical, electrical, corrosion, heat transfer and thermal cycle testing. Tests were configured to verify basic design features, subassemblies and various fabrication techniques.

To confirm the adequacy of the gas-side element designs and their fabrication, 1A4-style electrode and sidewall elements were installed in the 1A1 channel. These elements were tested for 22 hours under power conditions. A post-test inspection of the elements substantiated that the designs were adequate for service. The results from these tests are detailed in Section 5.2.

Prior to start of the 1000-hour POC test series, a final check of the 1A4 channel for test operations will be made. This step involves operation of the 1A4 channel for 50 electrical hours, followed by an inspection of the gas-side surfaces. In the unlikely event that any defective elements are detected during this "infant mortality" test/inspection, they will be replaced. The fully qualified 1A4 channel will then be reinstalled for conduct of the POC test.

5.1.5 Conclusions

Final design of an MHD channel for the Integrated Topping Cycle Program test has been completed. The channel was designed to be capable of 1.5 MW e power output and a lifetime of 2000 hours.

Emphasis was placed upon durability and reliability. Hence, specific measures were taken to design against channel damage due to electric faults, which are considered the most critical channel lifetime issue. Fault protection was addressed by limiting fault power, the use of interelectrode arc gaps, incorporation of corner joint ceramic, use of non-arc tracking wall liners and the utilization of plastic water manifolds.

The life-limiting issues associated with electrochemical corrosion and erosion of gas-side surfaces were addressed by the use of various materials with proven wear characteristics in a coal-fired MHD channel environment. Anode gas-side performance relies primarily on platinum caps to minimize wear due to electrical arcs and electrochemical corrosion. Backup to the platinum capping is provided by tungsten. Aluminum nitride ceramic caps are brazed onto the electrodes to electrically insulate the corner joint. Tungsten is the primary gas-side protection on the cathode wall and in the high electrochemical stress regions on the sidewalls. Gas-side protection on the remaining sidewall elements is furnished by using tungsten-copper.

Reliable operation of the 1A4 channel for 1000 hours in this severe environment requires that all components be built to specification. Hence, a high degree of rigor and attention to detail was imposed during channel fabrication.

Results from design confirmation tests conducted in the Avco/TDS Mark VII and 1A1 channels were used to confirm design choices and verify 1A4 channel component fabrication techniques. Pertinent findings from these studies, and from engineering development activities undertaken to evaluate channel components and fabrication techniques, were incorporated in the design and are utilized in fabricating the 1A4 channel.

5-16
Figure 5-16. Typical Channel Subassembly Work Flow Logic
Achieving a channel lifetime of 2000 hours is a challenging objective and difficult to verify. Confirmation that the 1A4 channel design fulfills the lifetime requirement can only be established during the 1000-hour POC testing.

5.2 1A4 DESIGN CONFIRMATION TESTS AT THE CDIF

During this reporting period, the 1A4 design confirmation tests at the CDIF were completed and the results 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 test 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. This demonstrates that most of the channel wear was electrochemical and arc related. As will be discussed, this approach may result in slight underestimates of element lifetimes.

Testing of the 1A4 prototypical elements accumulated 22 hours of coal-fired power generation with 19 hours at prototypical stress levels. A few of the channel elements were tested for longer periods. The total test times for these elements are noted in the discussions below.

5.2.1 Anode

Both slagging and nonslagging 1A4-style anodes were installed in the 1A1 channel. The difference in design features between the slagging and nonslagging test coupons lie with the use of boron nitride insulators. Nonslagging elements use full height (flush with the gas-side surface) interelectrode boron nitride insulators and the placement of full height insulators between adjacent electrode caps. These measures eliminate both transverse and axial foothold locations for the development of a wall slag layer. Slagging elements use recessed (0.090 inch from the gas-side surface) interelectrode boron nitride insulators and 0.075-inch wide gaps between adjacent electrode caps. Figure 5-5 shows a typical slagging 1A4-style anode.

Specific features of the anode design evaluated were: 1) the use of ZGS platinum versus pure platinum, 2) the use of aluminum nitride as an insulator at the sidewall-to-anode wall joint, and 3) the thickness of interanode insulators.

5.2.2 Sidewalls

Two sets of 1A4 style Z-bar sidewall coupons were distributed between the right and left forward sidewalls. They include elements having base materials of molybdenum and tungsten-copper (75W25Cu). These two materials represented primary and secondary materials choices at the time testing commenced.

The location and configuration of Z-bar coupons on the right forward sidewall are shown in Figure 5-17. These elements were designed to simulate the 1A4 design in the 1A1 channel as closely as possible. The main difference between this design and the 1A4 sidewall design is the use of three rather than four interior diagonal bars. This compromise, necessitated by 1A1 limitations, will have little effect on the outcome of the verification test results. Figure 5-18 shows cross-sections of the installed sidewall elements, defining both gas-side and element base materials.

Just downstream of the channel midsection, several rows of copper based sidewall elements were modified to include tungsten and molybdenum caps brazed onto copper bases. These elements were operated for 40 electrical hours prior to this test series, thus accumulating a total of about 60 electrical hours at the CDIF.
Figure 5-17. Location and Configuration of Right Forward Sidewall Z-Bar Coupons

Figure 5-18. Cross-Sections of Sidewall Test Elements
5.2.3 Cathode

A few 1A4-style cathode elements were fabricated and installed for evaluation. In addition, there were several elements of a slightly different design but with a 1A4-style tungsten cap. These were installed prior to this test series in the same region of the cathode wall and were operated for a total of 68 electrical hours.

5.2.4 Second Stage (Channel Inlet) Frame

A second stage frame was modified to incorporate the use of tungsten caps and to accommodate iron injection ports on the bottom wall. The frame was installed to evaluate the use of tungsten capping for the 1A4 nozzle section, as well as the effects, if any, of the changed iron injection port location on cathode wall polarization. A total of 27 hours was accumulated by this test section. It had coupons that simulate 1A4 elements that will be installed in the fringe field of the magnet. In this region the gas-side material wear for these surfaces will not be dominated by electrochemical corrosion accelerated by electric fields and arcing effects. Therefore, corrosion in this region will be less severe than in the electrode and sidewall elements.

5.2.5 1A1 Channel Test Results and Discussion

5.2.5.1 Anode

The limited amount of test time did not result in sufficient wear of the anode platinum caps to allow projections of anode lifetimes. For this same reason, comparisons of performance between the slagging and nonslagging elements were not conclusive. Lessening of grain boundary attack by the use of ZGS platinum was evident from microscopic examinations. In addition, it was apparent that interanode insulator spacing was an important variable. Thicker insulator gaps, i.e., 0.125 to 0.150 inch, traditionally enhance slagging, while the thinner gaps, i.e., 0.050 to 0.100 inch, provide enhanced protection of the anode upstream edge. The insulators that were 0.125 inch allowed a deeper penetration of arcs along the anode leading edge than did the thinner width insulators. It was evident that insulator gaps of the order of 0.075 inch eliminated aggressive attack of anode leading edge arcs into the groove along the anode leading edge. Based on these observations, an interelectrode gap of 0.090 inches was selected for the 1A4 anode wall as a compromise between arc protection of the electrode leading edge and providing a sufficient foothold for slag layer development.

Performance of the aluminum nitride insulators at the anode-to-sidewall joint was good. There was no evidence of spalling of the ceramic in the modified Z-wall section and the minor cracking noted was insufficient to degrade the thermal or electrical performance.

5.2.5.2 Cathode

Because of the limited number of test hours and few occurrences of high intercathode high voltage (arching) gaps during this series of tests, no wear rate data were gathered on the 1A4-style, tungsten capped cathodes. The lack of high voltage, arcing intercathode gaps is attributable to the use of iron oxide. Because iron oxide addition reduces slag polarization, the intercathode gaps were generally maintained in the 20 to 30 volt level throughout the test series.

The brazed-on aluminum nitride cathode-to-sidewall insulators showed no evidence of thermal or electrical degradation.

5.2.5.3 Sidewall

Gas-side sidewall test materials included tungsten-copper (75W25Cu) pressed and sintered composite, and wrought molybdenum and tungsten. The tungsten caps were brazed onto three base materials: tungsten-copper, molybdenum, and copper. Layouts and cross-sections of the 1A4-style, Z-bar sidewall elements are depicted in Figures 5-17 and 5-18.

Subsequent to testing, all of the sidewall coupon elements were removed and careful measurements were made of the material loss for each element. The results of these measurements are summarized in Table 5-1 for elements with either Mo or tungsten-copper base material. Most of the measurable material
TABLE 5-1. MEASURED WEAR DATA AND PROJECTED LIFETIMES OF Z-BAR SIDEWALL ELEMENTS

<table>
<thead>
<tr>
<th>Row</th>
<th>Base Material</th>
<th>Design</th>
<th>Measured Material Loss (cu inch X 10E-04)</th>
<th>Projected Lifetime (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>Mean</td>
</tr>
<tr>
<td>1</td>
<td>WCu</td>
<td>Solid</td>
<td>No Wear Observed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mo</td>
<td>Solid</td>
<td>No Wear Observed</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>WCu</td>
<td>Solid</td>
<td>8.4</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>Mo</td>
<td>Solid</td>
<td>26.0</td>
<td>14.9</td>
</tr>
<tr>
<td>3</td>
<td>WCu</td>
<td>Solid</td>
<td>14.0</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>Mo</td>
<td>Solid</td>
<td>25.9</td>
<td>11.9</td>
</tr>
<tr>
<td>4</td>
<td>WCu</td>
<td>W Cap</td>
<td>7.7</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Mo</td>
<td>W Cap</td>
<td>No Wear Observed</td>
<td></td>
</tr>
</tbody>
</table>

Losses were observed for rows 3 and 4 only. Rows 1, 2 and 5 had no significant material loss. A typical row of Z-bar elements as they appear subsequent to 19 hours at design test power is shown in Figure 5-19.

Lifetime estimates were made using the material loss measurements. The lifetimes were based on an assumption of linear wear rates. In the case of the solid tungsten-copper or solid molybdenum elements, a failed element was one that was projected to have material loss to breach the element water passage. For the tungsten capped elements, failure was assumed once wear was projected to impinge upon the base material. No credit was taken for additional lifetime contributed by the base material. This results in an underestimate of their lifetime and may be a substantial underestimate for elements not subjected to high voltage arcing gaps.

Lifetime estimates made in accordance with the above assumptions for the third and forth rows are listed in Table 5-1. Estimates for both molybdenum and tungsten-copper, as gas-side materials, and for tungsten caps on either tungsten-copper or molybdenum bases, are provided.

It is apparent from the table that the tungsten caps on the tungsten-copper bases have projected lifetimes in excess of those affixed to the molybdenum bases. No conclusive reasons are evident for this difference. Although the two base materials have different thermal conductivities, the resultant differences in gas-side surface temperatures are not sufficient to explain the accelerated tungsten cap material loss for the molybdenum based elements. There is also no reason to suspect integrity of the cap-to-base braze joint or to suspect that differences in water-side heat transfer coefficients contributed to the unequal wear rates. Although some interelement voltage data was available, it was insufficient to correlate voltages and wear.
rates. However, it is unlikely that voltage differences in these neighboring elements would be sufficient to account for the disparity in wear. This issue remains unresolved.

It should also be noted that molybdenum wear coupons placed elsewhere on the 1A1 channel sidewalls strongly indicate that molybdenum wear rates are nonlinear and decrease markedly as time proceeds. However, because the total test time was only 22 hours, and only a few of these elements were tested, these data were not used in establishing the molybdenum element lifetimes. This fact has been corroborated by tests of Mo cathodes in the Mark VII which showed a definite dependence of wear rate on surface temperature. The thinner the Mo element, the colder it operates. Thick Mo elements initially wear faster than 75W25Cu elements, but become more durable than 75W25Cu as they wear down.

Wear data for tungsten-capped, copper-based elements is also summarized in Table 5-1. These lifetimes were obtained from elements installed on the sidewall at the channel mid-joint.

5.2.5.4 Channel Inlet Frame

The limited amount of testing performed with iron oxide injection on the bottom wall indicated that this technique is as effective as the side-port injection technique used on the previous test series. Inspection of the tungsten capping on the inlet frame showed no evidence of wear.

5.2.6 1A1 Channel Test: Conclusions

Although cumulative test operations were short, some conclusions for the proposed designs can be made based upon the data:

1) The ZGS platinum capped anodes showed reduced grain boundary attack.
2) The interanode insulator width must be properly selected to minimize leading edge anode wear, yet provide a sufficiently wide gap for proper slagging.

Figure 5-19. Typical Row of Z-Bar Elements Subsequent to 20 Test Hours
3) No adverse design characteristics were evident for the anode, cathode, or inlet frame test coupons installed in the 1A1 channel.

4) The sidewall materials of choice, based upon results from 22 hours of testing with the 1A1 channel, were tungsten-copper and copper as base elements with tungsten caps and tungsten-copper for the uncapped sidewall elements.

5) The tungsten-copper elements and the tungsten-capped tungsten-copper elements had minimum projected lifetimes in excess of 2000 hours.

5.3 TUBE/PLUG BRAZE INVESTIGATION

5.3.1 Summary

Some 1A4-style elements that were installed in the 1A channel had leaks at the water tube braze joint. The root cause was attributed to interface corrosion between the braze joint and stainless steel tube resulting from loss of chromium from the stainless steel during the braze process. This difficulty was overcome by the use of a different braze alloy and change in the tube material. (The plug material was also changed.) The new tube material choice was brass, and the plug was made from tungsten-copper. Tests performed have shown that this design change resulted in well bonded, mechanically sound, leak free brazes.

5.3.2 Background

Hydrostatic tests performed on the 1A channel Z-bar sidewall coupons, after post-test channel disassembly, indicated that 18 of the 120 bars had minor leaks. The leaks were observed for water tubes on both the molybdenum and tungsten-copper bars. This event prompted an investigation into determining a cause for the leaks. In addition, this occurrence precluded submittal of a final design for the sidewall. Thus, proceeding with the sidewall fabrication required both an understanding of the problem root cause and implementation of corrective action. The activities undertaken to complete these tasks are outlined below.

5.3.3 Design

The 1A channel Z-bar elements were comprised of tungsten-copper (press-sintered, 75% tungsten-25% copper) and molybdenum (wrought) bases, with brazed 410 series stainless steel water tubes and plugs. The 410 stainless is a martensitic steel containing 12.25% Cr, with the following maximum values of other elements: 1.0% Mn, 1.0% Si, 0.04% P, 0.03% S, 0.15% C. The balance is Fe. Lucas-Milhaupt EF45 braze and Handy Flux were used to torch braze the water tubes and end plugs to the bases. (EF45 is comprised of 14% Ag, 15% Cu, 16% Zn and 24% Cd.) It has solidus and liquidus temperatures of 1125°F and 1145°F, respectively. The tube-to-base hole dimensions were sized to allow for a minimum 0.002-inch diametral clearance at the braze temperature.

5.3.4 Root Cause Investigation

As explained during the Critical Design Review, on 19 February 1991, the key to providing corrective action is determination of a root cause. The investigation results are presented below.

Close examinations of the water tube-to-base brazes, including cross-sectioning braze joints, were made. Microscopic inspections showed the braze fillets were peeling away from the stainless steel tube surface. Rusting and pitting of the stainless steel tubes adjacent to the braze fillets were also evident. When tubes were extracted from the bars, there was an appearance of a corrosion layer at the braze-to-stainless steel tube interface. This evidence, which was observed for both molybdenum and tungsten-copper base material designs, indicated that the failure was attributable to corrosive attack of the stainless steel-to-braze interface (see Figure 5-20).

5.3.5 Root Cause Finding

Discussions of this problem with Lucas-Milhaupt metallurgists and a review of the literature has resulted in an explanation for the observed interface corrosion and subsequent braze failure. When the
braze joint is heated in the presence of braze flux, chromium in the 410 stainless steel tube is selectively removed as chromic oxide, leaving a thin layer of chromium-free iron. The iron is anodic to the braze alloy and a crevice corrosion occurs at the braze-to-stainless interface. As discussed above, evidence of this was observed on the failed tubes. This failure mechanism is accelerated in a water environment, as water contains dissolved oxygen and chloride. The ferrous ions go into solution and diffuse to the braze fillet edge, resulting in disbond of the braze-to-tube interface.

Lucas-Milhaupt Company indicates that attack of the EF45 braze to 400 series stainless steels can result in a braze interface failure. Their data base reveals that this type of problem has resulted in braze failures as quickly as three days, or the braze joint may last years. As in any corrosion environment, corrosion rates are dependent upon many factors specific to a particular set of circumstances. Apparently our application allowed aggressive attack and premature failure of the brazed joint.

5.3.6 Corrective Action

Actions taken to provide a solution to the problem included the use of alternative braze alloys, braze techniques and/or water tube/plug materials. Several alternative measures were evaluated, and the final design choices are discussed below.

5.3.6.1 Tube/Plug Materials

The alternative tube material chosen for use with the tungsten-copper bases was brass (60% Cu, 39% Zn, 1% Sn). Although there were differential thermal expansion coefficients between the tungsten-copper bases and brass tubes, sound braze joints resulted. Because of their Zn content, brass tubes cannot be brazed in a hydrogen atmosphere or in a vacuum furnace, therefore the brazes were made by hand using a torch.
Plugs were made from the same type of material as the element bases, tungsten-copper. The results from numerous test brazes resulted in leak-free, well wetted plug brazes.

5.3.6.2 Braze Alloy

The braze alloy chosen was Lucas-Milhaupt B505. The brazes were accomplished using a torch and B-1 flux. (B505 is comprised of 50% Ag, 20% Cu, 28% Zn and 2% Ni. It has solidus and liquidus temperatures of 1220°F and 1305°F, respectively.) Lucas-Milhaupt B-1 flux was also recommended. Tests showed that B505 wetted both the tungsten-copper and brass. The braze alloy provided a braze joint that conformed to the guidelines specified by ASME Boiler and Pressure Vessel Code, Section VIII, for voids.

5.3.6.3 Braze Technique

Discussions of the braze techniques for the various combinations of tubes, plugs, bases and braze alloys are provided below. Each combination has its unique set of requirements that must be followed to yield a suitable braze. Because tungsten-copper bases are suitable for torch brazing, the use of brass tubes becomes a viable alternative to stainless steel tubes. As previously mentioned, tungsten-copper plugs were used in conjunction with the brass tubes, both being brazed with Lucas-Milhaupt B505 and B-1 flux. Several test brazes were made using this combination of materials and typical results are shown in Figure 5-21.

5.3.7 Final Design Selection

Brass tubes and tungsten-copper plugs, torch-brazed, using B505 and B-1 flux, are selected for use on the 1A4 tungsten-copper sidewall bar elements. Because of the Zn content, brass tubes preclude the use of vacuum or hydrogen furnace brazing, nonetheless, experience has shown that torch brazing with B505 can
be repeatedly and reliably made. In tests, these brazes had the same repeatability and integrity of brass-to-
copper brazes. A typical example is shown in Figures 5-22(a) and 5-22(b).

5.3.8 Tungsten-Copper Base Braze Joint Evaluations

Qualification of the braze joints included a series of inspections, evaluations and tests. The approach and results of this work are outlined below.

5.3.8.1 Hydrostatic Tests

Bars are hydrostatically tested at 450 psi and held for 5 minutes to determine if the braze is leak free and mechanically sound. This test is completed for every element. No leaks occurred in any of the tubes or plugs brazed using this technique. This includes fabrication test pieces, any of the 1A reworked tungsten-copper based elements, and any of the new tungsten-copper elements fabricated for use in the 1A channel Z-bar wall.

5.3.8.2 Wetting and Braze Voids

Wetting of the brazed surfaces was determined by visual inspection of the braze joint fillets and of the gap between the brazed materials. Inspection of the brass tube and tungsten-copper plug to the tungsten-
copper bases, using B505 showed good wetting and few voids. The minor number of voids observed met the allowable requirements specified by ASME Boiler and Pressure Vessel Code, Section VIII, Paragraph QB180 guidelines, i.e., 20% of linear dimension along a braze joint can have voids. This is also an industry standard. Anytime flux is used, 15 to 25% of the area can contain voids, depending upon the joint design.

5.3.8.3 Pull Tests

Test pieces were fabricated for pull tests. The test pieces were comprised of brass tubes brazed to tungsten-copper bases with B505 braze. The test elements were torch brazed using B-1 flux. An Instron machine was used to extract the tube from the base element. In every case the braze joint held and failure of the brass tubes occurred. The average force at failure for the six samples tested was 2285 pounds, the load at failure ranged from 2210 pounds to 2380 pounds.

5.3.8.4 Corrosion Tests

A typical brazed element has been placed in water to be observed for evidence of corrosion. Although none is anticipated, because of the experience with the materials of choice, the coupon will be periodically observed for evidence of corrosive attack at the braze joint interface. However, no evidence of corrosion at the braze joint interface has been observed after 300 hours.

5.3.8.5 Bench-Type Tests

Sidewall elements were installed in a plastic back-wall material, with the water tubes stressed by wedging the tubes to fit tightly into the plastic penetrations. These elements were thermally cycled 100 times with a welding torch. Each bar had a reduced water flow, about 0.5 gpm, to allow the bar to be heated to the greatest possible extent with the torch. Subsequent to these tests, the elements were hydrostatically tested and cross-sectioned at the braze joint. No evidence of braze joint degradation was observed.

5.3.8.6 1A Tests (Build No. 2)

Many of the 1A Z-bar molybdenum and tungsten-copper sidewall coupons were repaired or replaced with pieces fabricated using 410 stainless steel tubes/plugs brazed with B630 or B559, as appropriate. Both torch and hydrogen furnace brazes were used for repair of the tungsten-copper elements.

Some new elements were fabricated using brass tubes and tungsten-copper plugs. They were torch-brazed with B505 alloy and B-1 flux. These elements will be monitored for soundness as testing at the CDIF proceeds.
Figure 5-22. Photographs Showing Cross-Section of Brass Tube Brazed into Tungsten-Copper Base Element with Handy and Harman B505 Braze Alloy
5.4 SIDEBAR ATTACK BELOW THE GAS-SIDE SURFACE

5.4.1 Summary

Wear was observed below the gas-side surface on several 1A4 prototypical Z-bar elements. The wear might be best characterized as pitting, usually (but not always) on the upstream face of the element and always below the gas-side surface. The most likely cause of this wear is electrochemical corrosion. Accelerated corrosion is due to moisture between the bars. The source of this moisture appears to be leaky cooling water tubes. Because the cooling water tube problem has been rectified, pitting is not expected to occur in the future. In the prototypical channel, the sidebars will be encapsulated to prevent moisture from coming into contact with the gas-side.

5.4.2 Nature of Sidewall Wear

Pitting and a more general "cratering" was observed below the gas-side surface on several 1A4 prototypical Z-bar elements. Figure 5-23 is a photograph of the worst observed wear. Wear generally occurred on the anodic side of the sidebar, either on the long side or bottom of the bar.

The root cause of pitting is thought to be electrochemical attack with water acting as a conductor between adjacent elements. Figures 5-24(a) and 5-24(b) superimpose the locations of known cooling water tube leaks (denoted by an "L") and the locations of pitting on the sidewall, suggesting that the leaks are the source of the water-related wear. Condensation was also considered as a source of water in the channel, but this was discarded as calculations indicate that the minimum wall surface temperature (165 degrees Fahrenheit) is 30 to 45 degrees above the dew point calculated at channel operating conditions.

Other possible causes of wear are arc erosion and chemical corrosion. Arc erosion was considered because sidewall voltages can reach as high as 100 volts. However, this form of attack would only be expected if the boron nitride (BN) insulators were defective in the vicinity of observed pitting, and they were not. Electrochemical corrosion seems likely, as material loss was always found on the anodic surface.

Scanning Electron Microscopy (SEM) was performed on the prototypical sidewall coupons to characterize the pitting and to help ascertain its cause. Figure 5-25(a) is a photograph of a pitted W-Cu sidebar (20x). Figure 5-25(b) shows the same area in greater detail (150x). Nothing resembling arc erosion is seen in these photographs.

A series of elemental analyses for locations between the pitted surface and several millimeters below the surface had nearly identical material compositions (75W-25Cu, as expected), thus suggesting that material was not leeching from beneath the pitted surface. An advanced imaging photograph, Figure 5-26, was made at the pitted surface to look for a preferential loss of tungsten or copper.

5.4.3 Solution to Pitting Problem

The root cause of pitting was electrochemical attack with water acting as a conductor between adjacent elements. The source of this water, leaky cooling water tube braze joints, has been eliminated with new braze and tube materials as described in Section 5.3.

Further measures are also planned to eliminate the chances of electrochemical corrosion by preventing moisture contact with sidebar gas-side materials. These are to encapsulate the elements in RTV, and possibly to nickel plate them. This latter method is still under investigation.

5.4.4 Conclusions

An investigation into the cause of pitting observed in prototypical sidewall elements was conducted. Of the possible causes for the pitting; electrochemical attack, arc erosion, and chemical corrosion, only the first is supported by observations and supporting investigations.
Figure 5-23. Pitting on Prototypical Sidewall Element

PITT REGION

Figure indicates the location of, not the severity of, pitting. Bars with known water leaks are indicated by an "L".

Figure 5-24(a). Schematic of Left Sidewall and Water Leaks
5.5 WATER CORROSION: CURRENT STATUS OF 75W25CU TESTS

The water-side materials proposed for the 1A4 channel are copper and a press-sintered tungsten-copper composite (75% tungsten, 25% copper by weight). Water-side corrosion of both materials has been observed during 1A1 testing at the CDIF. These observations, and the requirement for greater than 2000 hours lifetime for 1A4 channel elements, precipitated an extensive and on-going water-side corrosion test program initiated in previous reporting periods (References 5-4 and 5-5). The final and most important goal of the test program is to establish the specific requirements for the CDIF Primary Cooling Water (PCW) system. The primary issues involve the pH and dissolved oxygen requirements. The water resistivity has been monitored and controlled and is well within the existing PCW system capability.

5.5.1 Background

In 1988 water-side corrosion was observed (Reference 5-6) in 75W25Cu sidewall end pegs at the CDIF. The pegs had only 40 power hours and thousands of hours under stagnant water conditions. Both the electrical and pH history were unknown. Macro and microscopic examinations showed a patchy greenish discoloration on an otherwise black tungsten oxide background. The origin of the greenish discoloration appears to be due to stagnant, oxygenated and carbon dioxide-saturated water conditions which react with the copper and produce the usual greenish malachite (CuCO$_3$*Cu(OH)$_2$) scale. Pits were observed in the 75W25Cu water hole inner surface which are a common form of corrosion due to leaching of the host into deionized water. In addition, copper pegs at the CDIF have shown general corrosion and pitting, characteristic of erosion/corrosion due to high velocity, low pH water. Again, the electrical and water chemistry environment was unknown. Subsequent measurements of the CDIF water system have
Figure 5-25. Scanning Electron Microscope Picture of Pitted Sidebar

75W - 25Cu SIDEBAR CORROSION AFTER 19 POWER HOURS 1A₁ CHANNEL
Figure 5-26. Scanning Electron Microscope Advanced Imaging Material Analysis: Pitted Surface
shown variations in pH with measurements as low as 5. Since corrosion has been observed in the proposed 1A4 materials, both in the Avco/TDS Mark VII and the CDIF 1A1 channel when the pH was uncontrolled, the test program has focused on determining the 1A4 channel pH requirements. In previous reporting periods, various materials have been evaluated under controlled pH conditions in a bench scale test apparatus. To adequately complete the test matrix, a high heat flux (representative of expected 1A4 operations) was deemed necessary to determine if the water-side corrosion on 75W25Cu will increase at elevated metal temperatures and also determine if a corrosion layer develops that impedes heat transfer. These results are reported in the following section.

5.5.2 High Heat Flux Test Results

A high heat flux test was recently completed for 75 hours of exposure to water at pH 7 with one meegohm resistivity. Water temperature was maintained at 140 to 160°F under an oxyacetylene torch which developed a heat flux of 400 W/cm² to simulate the MHD channel environment under power. In addition the water velocity was maintained at 30 feet/sec and the test specimen was held at 100 V anodic to sustain any possible electrochemical reactions for complete replication of channel conditions. Flow conditions produced a metal temperature of 400°F in contact with the water.

Upon completion of the test, the specimen was sectioned and studied using scanning electron microscopy (SEM) and scanning Auger microscopy (SAM). On the top surface of the water hole, the hottest region, there was a black surface film of W metal with 30% oxide and which was electrically conducting. This film was about 600 Angstroms thick and declined in oxide content to less than 5% as one progressed deeper towards the metal surface. The thinness of the film as well as its primarily metallic makeup mean that the film is not a barrier to heat transfer. In addition, during the test there was no significant increase in the metal temperature of the peg within the resolution of the experiment. This was further indication that a thermal resistance layer did not buildup on the surface of the water cooling passage.

On the bottom (cooler) surface, a similar film was observed but there were also some tubercular growths, about 1,000 to 10,000 Angstroms thick, and which were mostly metallic consisting of tungsten, oxygen, and carbon located only on the machine stress marks. These too were not deemed to endanger heat transfer, especially since they were on the bottom of the water passage.

Corrosion was too low to be measurable or to be life threatening: the water hole did not increase in size to the one mil resolution of the measurement. In fact, machining marks were still visible.

On the basis of this test, the water pH range was set to be 6.5 to 7.5 for acceptability for POC test conditions. Since corrosion has been observed in 75W25Cu both in Mark VII and 1A1 channel tests when pH was uncontrolled, it is felt certain that pH is the critical parameter defining acceptable performance of the material. However, controlling the dissolved oxygen content of the cooling water within acceptable power plant limits is standard industry practice and cannot be ruled out. In addition, a bench test in which tungsten-copper was placed in pH 7 water and exposed to the air showed a drop in pH to 3.2 over time. Thus, stagnant water conditions represent an uncontrolled corrosion environment, even with water initially at pH 7.

5.5.3 Water Corrosion: Conclusions

1) pH is a critical factor in the performance of 75W25Cu. Low pH is very likely to be the cause of the corrosion of 75W25Cu. It is recommended that the CDIF set the pH at 6.5 to 7.5.

2) Increased heat flux appears to reduce the deposits in the observed corrosion.

3) Stagnant water in contact with dissimilar metals can produce large changes in pH. Such conditions may produce elevated galvanic corrosion and thus will be avoided in the 1A4 channel.
5.6 CHANNEL FABRICATION STATUS

5.6.1 Introduction

The 1A4 channel and diffuser delivery schedule has been slipped to May 1992 because of a change in the selection of the sidewall base material from molybdenum to 75% tungsten-25% copper. This change in material selection was based upon results from the CDIF coupon tests that showed that the tungsten-copper material wears better than the molybdenum test elements. (These results were presented in Section 5.2 of this quarterly report.) The new channel fabrication and delivery schedule is shown in Figures 5-27 and 5-28.

5.6.2 Fabrication Status

The status of the fabrication activities are shown in Figures 5-27 and 5-28. The gray lines represent completed activities and the black lines designate uncompleted ones. As shown, fabrication of the supersonic diffuser and cathode are underway. Sidewall and anode wall procurements have started, but fabrication has not. Although some schedule variations are shown on the schedule, e.g., some activities are ahead and some are behind, the critical paths are not affected and the overall channel fabrication schedule remains on schedule and on budget.

REFERENCES FOR SECTION 5


5-3. ASME Boiler and Pressure Vessel Code, Section VIII, paragraph B 180.


### Channel and Diffuser Fabrication Schedule

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**Figure 5-27.** Channel and Diffuser Fabrication Schedule
Figure 5-28. Channel and Diffuser Fabrication Schedule (Continued)
6. CURRENT CONSOLIDATION SUBSYSTEM DESIGN AND FABRICATION
   (TASK 5)

The activities of this quarter dealt exclusively with the material procurement and construction of the full scale CDIF Current Consolidation Subsystem for the anode electrodes. The equipment is being built as specified in the CDR document. No significant changes have been made in the design, other than a few minor modifications that are summarized below.

6.1 RESISTIVE DIODE STACK CHANGES

The resistive consolidation scheme requires a network of diodes to prevent currents from circulating between electrodes. The CDR document showed these diodes as being tied common on one side. For example, on the channel anode side, the anodes of the diodes were all tied common. This simplifies the mechanical construction of the diode stack, since all of the diodes can be mounted to a common heat sink. However, this connection prohibits the use of "Christmas-tree" type resistive consolidation networks. At the request of Avco/TDS, the design was changed so individual diodes are electrically isolated and Christmas-tree type connections such as that shown in Figure 6-1 are possible.

Also, the single SCR device that switches in the resistive consolidation network was originally located in the power cabinets. MSE indicated that this arrangement required a long run of 1000 MCM cable from the power cabinet to the high voltage room. To accommodate the MSE request, the diode cabinet mechanical design was modified to include the hardware associated with the SCR device, eliminating the need to run the extra 1000 MCM cable.

6.2 DISPLAY SELECTION

The CDR document proposed color CRT-type display for the Central Control Room. This CRT was to be used to display all pertinent Current Consolidation status during operation. However, MSE personnel indicated that a CRT-type display will be affected by the high magnetic field level present in the Central Control Room. Thus an electroluminescent (EL) type display was purchased, Xycom Model 4870. This display is capable of presenting the same amount of information as the previous color CRT selection.

6.3 MULTIBUS COMPUTER CARDS

The CDR document discussed the use of Multibus II-type computer cards for data acquisition and control. This is still a relatively new technology that offers very high speed inter-board communication. However, due to the limited industry use of this new product line, it was decided to use Multibus I instead. Multibus I products are very well-established in industry for control and data acquisition. The slower bus communication speed of Multibus I will not compromise any of the control or data acquisition performance, as presented at the CDR.

6.4 PLANNED ACTIVITIES

Construction of the switch modules and the filter networks that makeup the consolidation circuits is presently underway. These circuits will be completed and tested in the near term. A preliminary test of the complete system should be complete by August.
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 of the prototypical power train components prior to fabrication of the actual prototypical hardware.

Test activities during the 15th quarter were divided into two distinct test series:

1) Accumulation of electrical hours on the prototypical channel elements which had been installed in the workhorse 1A1 channel.

2) Checkout of the operation of the continuous slag rejection system.

A total of 5.2 thermal hours and 2.5 electrical hours were accumulated during this reporting period. During the early portion of the quarter, the testing focused on the accumulation of electrical hours on the prototypical channel elements. The purpose of this test series was to accumulate sufficient electrical hours, approximately 50 hours, on the elements in order to evaluate wear characteristics of the various gas-side materials. This test series had been initiated during the 14th quarter and approximately 20 electrical hours (17 electrical hours at the correct operating condition) had been accumulated during that time frame. Only 2 additional hours were accumulated during the 15th quarter prior to terminating all electrical test operations due to the identification of a cooling water leak in one of the magnet coils. The channel was subsequently removed and the prototypical channel elements were inspected. Although the goal of 50 electrical hours was not achieved, sufficient data was accumulated in order to proceed with the channel CDR. The results of the investigation are reported in Section 5.2.

During the latter portion of the quarter, the testing focused on the functional and hot-fire checkout of the continuous slag rejector system. The initial installation of the slag rejector components had occurred during the 14th quarter. During the 15th quarter, the instrumentation and control system was completed which enabled continuous, automatic operation of the system. Only one checkout test of 1.6 hours was performed during this reporting period. Checkout testing will continue during the 16th quarter, however, the test operations will be thermal only (due to the magnet cooling water leak). Complete checkout of the system during power operations will not occur until September of 1991.

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

1) Installation of Phase II of the continuous slag rejector project which provided the controls and instrumentation necessary for continuous slag rejection.

2) Evaluation of low temperature acid corrosion on combustion subsystem components.

3) Inspection of the combustor second stage hardware, coal injector and the channel prototypical elements in order to provide wear and erosion/corrosion data required for the design/manufacturing of the prototypical combustor and channel subsystems.

A discussion of these activities is contained in Section 7.2 of this report.

7.1 WORKHOUSE 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 consolidation design
   - Channel design and material verification
I

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.

7.1.2 Approach

The approach for the workhorse testing is: 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) for checkout and verification of the component designs and modifications such as the Phase II slag rejector installation.

7.1.3 Test Summaries

The test activities during the 15th quarter can be divided into two distinct test series. The first, accumulation of 50 electrical hours on the 1991 prototypical channel coupons, was a continuation of a test series initiated during the 14th quarter. The second, checkout of continuous operation of the slag rejector, was initiated during the 15th quarter and will continue into the 16th quarter. 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.

7.1.3.1 Accumulation of 50 Electrical Hours on the 1991-Coupon Channel Build No. 1 (Table 7-2)

The 1991-coupon channel Build No. 1 is described in Section 5.2 of this quarterly report. As the 15th quarter began, the main objective of accumulating 50 electrical hours on the channel coupons had not been met. The tests conducted for this test series during the 15th quarter consisted of 91-MATL-07 and 91-MATL-08 (see Appendix A). These tests were run at prototypical electrical stress conditions (Reference Operating Condition No. 2) with iron oxide on the cathode wall to mitigate cathode wall nonuniformities. The secondary objective of this test series was to obtain a long duration continuous electrical operation test (16 to 24 continuous power hours) in order to evaluate the long term effects of iron oxide injection and to develop facility operational experience. Neither of the two objectives were met due to a variety of facility problems with frequent test aborts. These included:

1) Faulty wiring at the channel.
2) Coal blockage of the precombustor line and the CDIF primary coal injection vessel screen.
3) Plugged iron oxide lines.

Ultimately, this test series was discontinued when a water leak was discovered in the west half of the iron core magnet. Immediately after the diagnosis of the water leak, a UOR (Unusual Occurrence Report) was issued by MSE operations which ended power testing for the remainder of the 15th quarter. At that time, the decision was made to remove the channel and review the channel Z-wall and anode wall prototypical coupons. The information obtained during this review was utilized to select the 1A4 anode/sidewall design and was presented in Section 5.2 of this report. The Phase II slag rejector installation commenced following the removal of the channel.

7.1.3.2 Slag Rejector System Tests (Table 7-3)

Installation of Phase II of the slag rejector system was completed in April 1991 and is described in Section 7.2.3 of this report. Phase II provided for the installation of the control and instrumentation system
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**DOWN-TIME**

(1) PLANNED DOWN TIME

(2) REVIEW OF CHANNEL AND SECOND STAGE COMPONENTS

**RANKING**

A MET ALL TEST OBJECTIVES

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. 1991-COUPON CHANNEL 50-HOUR ELECTRICAL TEST SERIES

POWER AT CONDITION TOTAL = 18.8 HOURS
THERMAL TIME TOTAL = 28.6 HOURS
MAGNET TIME TOTAL = 22.3 HOURS

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<th>TEST RESULTS</th>
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<td>- L/W = 2.7, 12 port horizontal 0.36-inch diameter injectors</td>
<td>- 50 electrical hours on 1991-coupon channel</td>
<td>- New iron oxide injection scheme through ports along the bottom surface appears to work but requires slightly higher iron oxide flowrates: 4 to 5 lb/min</td>
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<td>- CFC heat loss = 6.5 to 7.0% of thermal input</td>
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<td>- Utilizing a single iron oxide port (versus the nominal two ports) does not mitigate cathode voltage nonuniformities</td>
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<thead>
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<th>TEST DESIGNATION</th>
<th>ACTUAL TEST CONDITIONS</th>
<th>HRS POWER AT CONDITION</th>
<th>TEST STARTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST</td>
<td>DATE</td>
<td>N/O</td>
<td>PREHEAT</td>
</tr>
<tr>
<td>91-CHEK-02</td>
<td>01/17/91</td>
<td>0.76</td>
<td>1200/2900</td>
</tr>
<tr>
<td>91-MATL-04</td>
<td>01/23/91</td>
<td>0.76</td>
<td>1200/2900</td>
</tr>
<tr>
<td>91-MATL-05</td>
<td>01/24/91</td>
<td>0.76</td>
<td>1200/2900</td>
</tr>
<tr>
<td>91-MATL-06</td>
<td>01/20-30/91</td>
<td>0.76</td>
<td>1200/2900</td>
</tr>
<tr>
<td>91-MATL-07</td>
<td>02/05/91</td>
<td>0.76</td>
<td>1200/2900</td>
</tr>
<tr>
<td>91-MATL-08</td>
<td>02/07/91</td>
<td>0.76</td>
<td>1200/2900</td>
</tr>
</tbody>
</table>

*Only 2 tests which occurred during the 15th quarter
TABLE 7-3.  1991 SLAG REJECTOR CHECKOUT TEST

<table>
<thead>
<tr>
<th>SECOND STAGE CONFIGURATION</th>
<th>TESTING OBJECTIVES</th>
<th>TEST RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- L/W = 2.7, 12 port horizontal 0.36-inch diameter injectors</td>
<td>- Primary: slag rejector checkout Secondary: seed utilization</td>
<td>- Preliminary checkout test only</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST DESIGNATION</th>
<th>ACTUAL TEST CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST DATE</td>
<td>N/O</td>
</tr>
<tr>
<td>91-SREJ-01</td>
<td>04/29/91</td>
</tr>
</tbody>
</table>
necessary for continuous operation of the slag removal system. Functional checkout of the system was completed prior to hot-fire (thermal) operation. The functional checkout included completion of the System Operating Test Procedure (SOTP) which required operation of the slag rejection system at 8 kV. No problems were noted during this phase of the checkout. Only one hot-fire test was conducted during this quarter (see Appendix A). The automatic sequencing of the slag rejection system did not operate correctly during this test and the system was operated manually. Problems with the automatic cycle appeared to be the result of flow switch fluctuations which occurred at the beginning of the water refill cycle. A time delay was installed in the sequence in order to mitigate this problem. Testing will continue during the 16th quarter.

7.2 CDIF HARDWARE ACTIVITIES

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

1) Evaluation of low temperature acid corrosion during combustor operation and downtime.
2) Inspection of second stage combustor components in order to determine the susceptibility to corrosion of the various braze alloys and stainless steel cladding materials currently in service.
3) Inspection of the wear characteristics of the main stage coal injector.
4) Installation of Phase II of the continuous slag rejector project which provided the controls and instrumentation necessary for continuous slag rejection.
5) Removal and inspection of the prototypical anode and sidewall channel elements. The sidewall elements were repaired (coolant tubes/plugs rebrazed) or replaced by Avco/TDS. The sidewall and anode elements were reinstalled in the 1A1 workhorse channel at the end of the quarter.

The following sections will provide additional detailed information on these activities.

7.2.1 Combustion Subsystem Activities

7.2.1.1 Low Temperature Acid Corrosion Investigation

The low temperature acid corrosion investigation was initiated during the 14th quarter and continued during the 15th quarter. The 14th quarter investigation focused on evaluation of the acid corrosion which had occurred on the backside (cold side) of the air inlet "filler" section. The filler section is the component which transitions from the coal-fired precombustor to the first stage. It is installed within the first stage air inlet section and hence simulates the prototypical panel-in-shell configuration. The top and bottom surface of the filler were constructed from SA-387 low-alloy steel (prototypical panel material). At the end of the 14th quarter, the filler was removed from service and inspected in order to quantify the acid corrosion. Results of this inspection were reported in Section 4 of this quarterly report. In brief, extensive pitting of the backside surface was identified on both the top and bottom plates constructed from SA-387. The pits on the bottom surface were 40 to 60 mils deep, the top surface pits were 20 to 30 mils deep. The operating time on this component was relatively short (~90 thermal hours) compared to the overall downtime while this component was installed (~4000 hours). It was therefore suspected that the extensive pitting had occurred during downtime as a result of acid condensation on the cold surfaces. In order to confirm this theory, a new filler section was installed during the 15th quarter. The "new" filler section was an existing component constructed from Inconel 625. "Coupons" of various materials and/or coatings were tack welded to the backside of the top and bottom plates in order to evaluate the corrosion resistance of the various materials. The "coupon" filler section was described in detail in Section 4 of this report.

Immediately after each test, the bottom plate of the filler is connected to a 200°F cooling water supply in order to "dryout" any condensate on the backside of the plate. The top plate is connected to the city water supply which typically operates at 50°F. Two type K thermocouples, one in the bottom plate and one in the top plate, are utilized to confirm the post-test temperatures of the coupons. The coupon filler will be removed following the May 1991 CDIF shutdown and the corrosion behavior of the top plate and bottom plates will be reviewed. The purpose of this evaluation is 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.

2) to determine:
   - if the majority of the corrosion occurs during actual combustor operation or during downtime
   - 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.

In addition to the filler corrosion test, additional acid corrosion evaluations were performed during the 15th quarter. These tests included: 1) installation/evaluation of absorbent material in various locations of the slagging stage and precombustor in order to determine the pH of the condensate as a function of location, 2) wedge coupons installed at the interface of the filler section and slagging stage which can be removed immediately post-test and evaluated for any signs of corrosion which occurs during combustor operation (i.e. these coupons are not exposed to downtime corrosion products). Determination of the pH of the condensate as a function of precombustor/combustor axial location was completed during this quarter. Figure 7-1 identifies the pH of the condensate in the various regions. Additional information of this analysis was provided in Section 4 of this report. The results of the removable wedge coupon corrosion tests will be reported next quarter.

### 7.2.1.2 Second Stage

The second stage was removed and each frame was reviewed for corrosion. At the interface between the braze material and the copper there is a characteristic corrosion area. The purpose of the review was to
determine the susceptibility to corrosion of the various braze alloys and stainless steel cladding materials currently in service. This investigation resulted in the following conclusion: 1) BAu-4 brazing alloy (gold-nickel) is less susceptible to corrosion than BAu-8 (silver-copper) and 2) stainless steel 446 is less susceptible to corrosion than stainless steel 330. This information, in conjunction with various bench scale brazing test results, was utilized to select the prototypical second stage cladding material (SS 446) and braze alloy (BAu-4). Table 4-4 summarizing this information was presented in Section 4. The second stage was re-stacked to the same configuration as that removed and is shown on Figure 7-2.

7.2.1.3 Main Stage Coal Pintle

The main stage coal pintle was removed and inspected in order to quantify wear characteristics. The primary region of wear on the pintle occurs within the turning radius (see Figure 7-3), and an erosion resistant material is installed in this region. Various materials (ferro-tic, SS 310, stellite) have been utilized in this region. The current wear ring material, stainless steel 446, provided the best erosion resistant characteristics to date. Details on the erosion results were presented in Section 4. A spare coal pintle was utilized for the testing that occurred while the wear ring was being inspected. The original pintle and wear ring will be reinstalled during the next downtime in order to continue to accumulate data on erosion characteristics as a function of time.

7.2.1.4 Precombustor Coal Pintle

The precombustor coal pintle was also replaced. This was done to install an enhanced pintle locking method. During previous testing, it was noticed that the set-screw locking of the pintle gap was not a reliable method to keep the pintle gap set correctly. Therefore, a weld-on locking area was included to lock the gap in place.

7.2.1.5 Headend Plate

A newly refurbished end plate (S/N 05) was installed in place of the headend plate. The headend plate (S/N 03) had in excess of 300 hours of thermal operation and was replaced due to the many leak repairs required to keep it serviceable. The headend plate (S/N 03) was built during the original combustor fabrication in 1984 and did not incorporate the manufacturing improvements, primarily in the area of weld joint preparation and weld penetration, that had been utilized during later hardware fabrication activities. The refurbished end plate (S/N 05) was also built during the original combustor fabrication in 1984/85, and hence does not incorporate improved manufacturing/welding techniques. The refurbishment consisted of installing a new Inconel liner on the inner bore and re-welding slag retention pins on the gas-side surface. The Inconel liner on the gas-side surface was not replaced. It was dye penetrant inspected and appeared to be in good condition.

7.2.2 Channel Hardware Activities

The channel was rebuilt during the 14th quarter in order to incorporate prototypical material elements and 1A14 dimensionally identical (0.7-inch pitch) coupons on the anode, cathode and sidewalls. These elements and the channel configuration were described in detail in Section 5.2 of this report. During this quarterly reporting period, the channel was disassembled following the accumulation of 22 hours of coal-fired power generation. The prototypical elements were removed and inspected. The results of this investigation were reported in Sections 5.2 and 5.3.

Several of the prototypical sidewall elements had leaks at the water tube braze joint. An intensive investigation was performed by Avco/TDS in order to determine the cause of the leaks and implement corrective action. This investigation was completed during this reporting period and the results were presented in Section 5.3. In brief, interface corrosion between the braze joint and the water tube material (410 stainless steel) was the root cause of the leaks. The corrective action was to utilize a different braze alloy and, in the cause of tungsten-copper elements, change the water tube (and plug) material. The new tube material is brass and the plug is tungsten-copper for the tungsten-copper base elements. The 1A1 prototypical elements were subsequently repaired or replaced. The repaired elements utilized 410 stainless
### Stack Position

<table>
<thead>
<tr>
<th>Stack Position</th>
<th>Item Description</th>
<th>P/N</th>
<th>S/N</th>
<th>C.C. Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ni-200 Adapter</td>
<td>X755640 1</td>
<td>01</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>&quot;Easy Torque&quot;</td>
<td>X431942-2</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1st Cu Frame</td>
<td>X431942-1</td>
<td>02</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Reworked Common</td>
<td>X431944-RW</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3pc 446 SS lined</td>
<td>X439103-1</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Ox. Inj. Frame (446 lined)</td>
<td>X438123-1D</td>
<td>42</td>
<td>90°</td>
</tr>
<tr>
<td>7</td>
<td>Ox. Inj. Spacer (grooved)</td>
<td>X438122-1</td>
<td>34</td>
<td>90°</td>
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<tr>
<td>8</td>
<td>3pc 446 SS lined</td>
<td>X439103-1</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>9</td>
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<td>12</td>
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<td>X439103-1</td>
<td>32</td>
<td></td>
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<tr>
<td>13</td>
<td>3pc 446 SS lined</td>
<td>X439103-1</td>
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</tr>
<tr>
<td>14</td>
<td>3pc 446 SS lined</td>
<td>X489103-1</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Ox. Inj. Spacer (grooved)</td>
<td>X438122-RW</td>
<td>18</td>
<td>90°</td>
</tr>
<tr>
<td>16</td>
<td>Rework Common</td>
<td>X431944-RW</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>B/L Frame</td>
<td>X438765-RW</td>
<td>25</td>
<td>90°</td>
</tr>
<tr>
<td>18</td>
<td>Iron Oxide Injector (Avco)</td>
<td>MHD-22931</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1) Frame 18 configured for additive injection through 2 each 0.19" ports across bottom with nitrogen around the port. All other ports are plugged.

2) Cooling water delta T's located at frames 4, 6, 8, 12 & 17 for L/W=2.7

3) Rod length 4 @ 37", 4 @ 32".

---

**Figure 7-2. CFC Second Stage Configuration - CDIF - 50SS - 910107**
Figure 7-3. Schematic of Met Stages Coal Pindle Indicating Where Erosion Resistant Material is Utilized

Steel water tubes/plugs and a new braze alloy (B630 or B559 as appropriate). Both torch and hydrogen furnace brazes were utilized for repair of the tungsten-copper elements.

Some new tungsten-copper elements were fabricated using brass tubes and tungsten-copper plugs. They were torch-brazed with B505 alloy and B-1 flux. The repaired elements and new elements were installed in the 1A1 channel during this reporting period. Thermal cycling of these elements during the 16th quarter testing will be used to confirm that the braze joint leak problem has been solved. There will not be any electrical testing during the 16th quarter due to the water leak in the magnet coil.

7.2.3 Slag Rejector Activities

The installation of the TRW slag rejector was divided into 3 phases for installation at MSE:

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 this 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. The slag rejection system was designed under a previous contract and was delivered to the CDIF in 1988.
Figure 7-4. Slag Rejection System Schematic
The Slag Rejector System (SRS) provides for the following on-line functions:

1) Reduces slag particle size to 1/4 - 1/2 inch by passing oversized pieces through a grinder.
2) Enables the transfer of processed slag at pressure (6 atmospheres) and high electrical potential (up to -10 kV DC) to atmospheric pressure and ground potential (facility slag tank).
3) Monitors electrical current leakage between the MHD power train and SRS collection tank and between the SRS collection tank and facility ground.
4) Electrical hardline connections via high voltage relays between slag transfer points during transfer operations.

The SRS utilizes the existing CFC slag tank modified to allow the installation of a slag grinder internally (Figure 7-4). The outlet of the slag tank is connected to a lock hopper (denseveyor) via an 8-inch pipe. The denseveyor is equipped with a dome valve at the inlet to permit pressure isolation from the slag tank during transfer operations. The outlet of the denseveyor is connected to redundant 6-inch ball valves, isolating the contents of the denseveyor from atmospheric pressure, and an intermediary slag collection tank. The collection tank provides the means by which slag can be transferred from the pressurized power train system to an atmospheric environment while remaining at the same electrical potential as the power train. The outlet of the collection tank is fitted with a 12-inch dome valve, which controls the discharge to the facility handling system. A 2-inch (minimum) air gap is necessary between the outlet of the collection tank discharge valve and the facility interface to ensure electrical isolation. The variability of the slag water conductivity precludes the use of a hardline connection. Two high voltage switches are used to electrically switch between the combustor voltage and ground.

During the Phase II installation of the slag rejector project, the System Operating Test Procedure (SOTP) was written. The procedure provided for checkout testing of the slag rejector in manual and full automatic mode. The procedure checked out the valve function, switch function and operation with high potential test apparatus at 8 kV (which is the usual value during voltage testing of the test train). The electrical isolation to ground for the entire test train including the slag rejector was found to be 20 K-ohms. This value is consistent with new unslagged channel readings at 8 kV.

The only test operating the slag rejection system this quarter was 91-SREJ-01, which was run on April 29, 1991. This test showed that the logic for the denseveyor vent cycle must ignore the venting flow switch until 15 seconds prior to denseveyor refill. This change to the logic was made, and a successful thermal test was accomplished on May 1, 1991.

7.2.4 CDIF System Activities

7.2.4.1 Primary Cooling Water System

The primary cooling water system (PCW) at the CDIF has conductivity control but no chemical control of pH or dissolved oxygen. A set of coupons representative of the combustor and channel subsystem water-side materials was installed in the CDIF PCW system during the 14th quarter. The results of that investigation were reported in Appendix C of the 14th quarterly. Additional coupons were installed in the CDIF PCW during this quarter. Based on the channel CDR held in February, the water-side material on the sidewalls is 75/25 tungsten-copper. These coupons were installed in the PCW to continue the accumulation of corrosion rate data on this material.

Tungsten-copper (75W/25Cu) water corrosion test coupons were installed in the CDIF PCW system on 2/26/91 in four locations. The test setup is similar to that reported last quarter and is shown on Figure 7-5. Identical W-Cu coupons were installed and selectively removed at timed intervals to obtain corrosion rate versus time information. Very little water chemistry sampling was performed during the period, but the pH was found to vary between 5.8 and 6.2.

Four coupons were removed with varying degrees of exposure time to the PCW and varying water flow times. The data for these samples is presented in Table 7-4. The method for corrosion rate determination is
FIGURE 7.5. Coupon Flow Test Schematic

TABLE 7-4. CDIF PCW W/CU COUPON CORROSION RESULTS (4/15/91)

<table>
<thead>
<tr>
<th>COUPON ID</th>
<th>INITIAL Wt (g)</th>
<th>END Wt (g)</th>
<th>DELTA Wt (mg)</th>
<th>TIME IN WATER (HR)</th>
<th>TIME AT VELOCITY (1) (HR)</th>
<th>CORROSION RATE (2) (MPY)</th>
<th>PERCENT OF TIME WATER FLOWING</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21.6048</td>
<td>21.5908</td>
<td>14.0</td>
<td>81</td>
<td>0</td>
<td>18</td>
<td>0%</td>
</tr>
<tr>
<td>B</td>
<td>21.2975</td>
<td>21.2220</td>
<td>75.5</td>
<td>367</td>
<td>58</td>
<td>2.2</td>
<td>16%</td>
</tr>
<tr>
<td>C</td>
<td>20.8224</td>
<td>19.9566</td>
<td>865.8</td>
<td>1170</td>
<td>424</td>
<td>7.9</td>
<td>36%</td>
</tr>
<tr>
<td>F</td>
<td>21.1445</td>
<td>20.4593</td>
<td>685.2</td>
<td>803</td>
<td>366</td>
<td>9.1</td>
<td>46%</td>
</tr>
</tbody>
</table>

Data from Appendix C of 14th Quarterly Report.

Notes:
1) Velocity estimated to be approximately 10 to 12 fps.
2) W/Cu corrosion rate determination: mpy = wt loss (g)/exposure time (hr) * (10,664)

described in Appendix C of the 14th Quarterly Report. From the data, there does not appear to be a linear relationship between corrosion rate and exposure time in the PCW.

The only significant result is that the corrosion rate appears to increase linearly with the percentage of time the water is flowing as follows:
<table>
<thead>
<tr>
<th>Coupon ID</th>
<th>Corrosion Rate (mpy)</th>
<th>% of Time Water Was Flowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.8</td>
<td>0%</td>
</tr>
<tr>
<td>B</td>
<td>2.2</td>
<td>16%</td>
</tr>
<tr>
<td>C</td>
<td>7.9</td>
<td>36%</td>
</tr>
<tr>
<td>F</td>
<td>9.1</td>
<td>46%</td>
</tr>
<tr>
<td>From Appendix C of 14th Quarterly Report</td>
<td>20.2</td>
<td>97%</td>
</tr>
</tbody>
</table>

These values are plotted on Figure 7-6. This could indicate that static local conditions are different chemically than flowing conditions.

There are currently four coupons installed in the PCW system. We will continue to accumulate time on these W-Cu coupons. The results will be reported when more data on PCW pH and dissolved oxygen content become available. Test work will be repeated once MSE implements pH control and dissolved oxygen control (if required).

7.2.4.2 Iron Oxide System

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

7.2.4.3 Coal System

A static screen was installed between the coal filter receiver and the storage injector. This screen was to replace the screen in the primary injector which, when plugged, requires removal of many large bolts in order to gain access to the screen. The screen installed under the filter receiver plugged quickly during the
initial test phase, and further confirmed the need for a vibrating screen in this location rather than a static screen.

7.2.4.4 Seed System

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

7.2.4.5 Magnet

The iron core magnet developed a cooling water leak between the conductor and the insulation. This leak was well documented by MSE and a UOR (Unusual Occurrence Report) was filed. There are currently two competing solutions:

1) To design and install an electrical jumper in order to electrically isolate the affected coil section.
2) To repair the leak in place by injection with a thermosetting resin system.

Currently the DOE has not indicated which method will be employed nor when the repair will occur. Thus, there was not any power generation during testing in the latter part of the 15th quarter, nor will there by any during the next quarter.

7.3 TEST PLANS

The test plans for future quarters is shown in Figure 7-7, "ITC CDIF Test Schedule". Specifically for next quarter, the CDIF testing will emphasize slag rejector Phase II checkout.

Test time will be limited to two weeks next quarter due to the 4-month downtime required for data acquisition system (DAS) installation. This downtime is scheduled to start on May 18, 1991, and includes the following 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.

During the middle 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 quarter is as follows:

Primary Objectives

1) Combustion subsystem checkouts including:
   a) Continuous slag rejection at voltage
   b) Rectangular second stage
   c) Slag tank/rejector/vent line modifications

2) Checkout of the Westinghouse supplied anode current consolidation cabinet including various configurations of the forward PTO and transition regions.

3) Checkout of Avco/TDS current controls as consolidators on the aft PTO including various configurations of the PTO and transition regions.

4) 50-hour continuous electrical power test.

5) Facility checkout test
   a) DAS system operation
   b) Slag removal system operation
FIGURE 7-7. ITC CDIF TEST SCHEDULE AS OF 04/22/91

ITC TEST GROUPS (THERMAL TEST HRS)

ITC FACILITY ACTIVITIES (CONSTRAINTS)

22 Hour Cont. Elec. Power Generation Test
Testing That Takes Precedence

DVT CHANNEL & DURATION

ITC TEST GROUPS - CONFIRMATION TESTING IS NUMBERED

FY-1991

(1) Sidewall & Anode Wall Confr.
(2) C/O Cont. Slag Rejection
(3) Finer Coal Tests Confirmation
(4) Eastern Coal*
(5) Seed Utiliz/Efficiency
(6) Formate Seed Tests
(7) 50 Hour Cont. Elec.
(8) Tailored Coal Testing*
(9) Checkout DAS & Slag Removal System
(10) Checkout Anode CC
(11) Aft PTO Studies

FY-1992

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

FY-1993

DVT Channel Plus Duration Testing

WORK START DATE CONSTRAINTS
(Y) = DAS ARRIVAL GUARANTEED, CURRENT CONSOL. CIRCUITS
02 TANKS ARVL GUARANTEED
(Z) = ARRIVAL OF LPCS, COMBUSTION SUBSYSTEM

CDIF FACILITY ACTIVITIES

1 = Z-BAR WALL INSTALLATION
2 = C.S.R. PHASE 2
3 = C.S.R./S.R.S. PHASE 3
4 = PIPING TIE-IN 50 HOUR O2, N2
5 = 1A4 WIRING/PLUMBING
6 = RECT. S.S. INSTALL
7 = DAS INSTALLATION
8 = INSTALL CURRENT CONSOL. ANODE CABINET
9 = INSTALL LPCS
10 = INSTALL POC COMBUSTOR
11 = CURRENT CONSOL. COMPLETION
12 = INSTALL 1A4 & INSULATE COMB.
13 = R&R 1A4 FOR DURATION

* Not Budgeted
c) Iron oxide modifications

d) Transfer from new O2 storage on-line

e) Seed modifications

Secondary Objectives

1) Seed utilization (continuation of testing initiated during the 16th quarter including power generation)

2) Feed system sweeps ($\phi_1$, $\phi_2$, N/O, %K, iron oxide)
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, activities related to a variety of performance analysis and modeling tasks continued. In the combustion subsystem, efforts continued to focus on understanding and improving the current levels of slag recovery and seed utilization achieved by the combustor. A separate report on the combustor slag recovery issue is expected to be distributed in the next several months. In order to further understand the factors which affect combustor seed utilization, a series of seed characterization tests will be conducted at the CDIF concurrent with the slag rejector checkout tests. Tests will focus on obtaining a complete baseline characterization, as well as on assessing the effects of increased seed injection velocity and increased deswirl gas temperatures. Tests will be performed at three different seeding levels and include numerous seed-off transients. The results will be reported in the next quarterly report. In addition to seed utilization and slag recovery, analytical support was also provided in the areas of slag rejection system operation, precombustor operation, and oil burner design modifications.

Channel data analysis activities continued in support of prototypical coupon testing at the CDIF. In Section 8.1, an evaluation of channel wall slagging behavior encompassing the last three test series at the CDIF is presented. During the January-February 1991 test series, two sets of anode coupons (with and without recessed insulators) were individually cooled and instrumented. The results of these tests are presented herein. The Z-bar sidewall coupons were also extensively instrumented with voltage transducers to provide information on gap voltages and channel sidewall wear characteristics. An analysis of this data is presented in Section 8.2.

Finally, in Section 8.3, analytical and experimental activities are described which focused on understanding the electrical behavior of the segmented diffuser wall section that will be installed concurrent with the 1A4 channel. To predict the electrical behavior of the unloaded diffuser segments, an analytical model was developed for a generic unloaded region at the back of an MHD channel. The trends predicted by the model were checked against data obtained from a 1A1 test at the CDIF where the last 10 anodes were left floating. Once the trends had been verified, an investigation was carried out on the Mark VII workhorse channel to examine the effect of various bleed resistor profiles on an unloaded rear section of the channel. This provided important qualitative trends which will guide the selection of any necessary bleed resistors at the CDIF.

8.1 EVALUATION OF CHANNEL WALL SLAGGING

The purpose of this study was to develop a data base to help diagnose channel wall slagging behavior during steady state combustor operation. Wall slagging in the channel is important as it reduces channel heat fluxes and boundary layer voltage drops, and provides erosion protection. In order to extend anode lifetime, an ungrooved platinum-capped anode has been selected for the ITC Proof-of-Concept tests. However, to help promote slagging, the interelectrode boron nitride insulators are slightly recessed below the electrode surface. During the January-February 1991 test series, ungrooved anode coupons were installed with and without recessed insulators at selected channel locations to determine whether recessing
the insulator has a noticeable effect on slagging behavior. Two groups of these test coupons were installed with separate cooling circuits in order to determine local heat fluxes. These heat fluxes were then utilized as a diagnostic to determine the degree of local wall slagging.

In order to aid in the interpretation of the data, a review of nominal channel heat fluxes was performed for both startup and steady state combustor operation. Conclusions about the degree in which channel walls slag can be made based upon local nonuniform heat flux distributions in the channel, as well as the level of drop off in heat flux from startup to steady state operation.

8.1.1 Nominal Channel Heat Fluxes

The CDIF tests included in this study are shown in Table 8-1, along with their nominal operating conditions. Various channel locations have been instrumented to determine channel heat fluxes. These locations are: 1) the front flange of the channel, 2) the front half and rear half of the anode and cathode, and 3) the front third, middle third, and rear third of the left and right sidewalls. Heat fluxes have been tabulated during combustor startup as well as during steady state operation, and the results are shown in Tables 8-2 through 8-4. Comparisons are made between heat fluxes in the same general location for the purpose of determining nonuniformities due to differences in wall slagging. Furthermore, comparisons are made between heat fluxes at startup and at steady state conditions for the purpose of determining whether wall slagging is occurring or not during this transition period.

At combustor startup, the average anode heat flux in the front half of the channel is typically about 170 to 190 W/cm², whereas the startup cathode heat flux is generally in the 130 to 150 W/cm² range. This difference in heat flux appears to indicate that the cathode wall in the front of the channel in general had better slag coverage at the start of the test than the anode wall for the tests surveyed. Unlike the front half of the channel, rear anode and cathode startup heat fluxes are closer in value, typically running in the 100 to 110 W/cm² range. Startup heat fluxes on the left and right sidewalls also agree well with each other in general, with values of 200 W/cm² in the front, 150 W/cm² in the middle, and 100 W/cm² in the rear of the

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<th>PHI 2</th>
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<th>%K</th>
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*TEST PERIODS DURING WHICH CHANNEL WAS NOT REMOVED FOR OBSERVATIONS OR MAINTENANCE

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|          | ALL TESTS | -8       | -42      | -14      | -11      | -20      | -28      | -29      | -27      | -44      | -43      | -42      | -31      |
## TABLE 8-4. HEAT FLUXES DURING STEADY STATE WITH POWER ON (W/cm²)

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### Average Change in Heat Flux from Power Off to Power On (%)

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channel. There are, however, some exceptions to this, particularly for the middle sidewall section during the test series that began with test 90-WEST-3. In this case, the startup heat fluxes for the left middle wall are significantly higher than the right wall.

Steady state heat flux results with seed on but with power off are shown in Table 8-3. Typically, the front anode heat flux decreases by approximately 40% relative to its startup value, indicating a significant improvement in slag coverage. The front cathode wall and the front sidewalls decrease by only 15 to 20% during the same time period. During steady state operation without power, both the cathode and anode walls have heat fluxes in the 110 to 130 W/cm² range. Thus, although the front cathode wall appears to have better slag coverage at the beginning of a test, by the time the heat fluxes reach steady state values, they appear to indicate similar slag coverages for both walls.

The response of the rear electrode walls is different than that observed for the front walls. Typically, a 40 to 45% reduction in heat flux is observed for the cathode and sidewalls between startup and steady state operation, indicating a significant improvement in slag coverage. The anode wall, while starting at the same heat flux level as the cathode wall, at times appears to have difficulty slagging to the same degree as the other walls, remaining at the 90 to 100 W/cm² level, while the adjacent walls have heat fluxes in the 50 to 60 W/cm² range.

Heat fluxes for the left and right sidewalls were found to agree well with each other down the length of the channel during this steady state period indicating similar wall slagging conditions. Typical values for the sidewall heat fluxes are 170 W/cm² in the front, 110 W/cm² in the middle, and 60 W/cm² in the rear of the channel. This corresponds to a 15% lower heat flux in the front of the channel, a 25% lower heat flux in the middle, and a 40% lower heat flux in the rear. The large decrease in the sidewall heat flux in the rear of the channel appears to indicate that significant wall slagging is occurring during startup.

The channel heat flux results shown in Table 8-4 are for steady state conditions with power "on". Comparing the power "off" results in Table 8-3 with those in Table 8-4 indicate that the heat flux on the anode and cathode were significantly affected by power. The increase in channel heat loss for power "on" conditions have been attributed to various power dissipation mechanisms near the electrode walls, including boundary layer voltage drops, arcing, and current leakage through the slag layer. Generally, the heat flux was observed to increase by about 50%. The rear anode heat flux, however, showed a variable increase which appeared to correlate directly with the level of decrease in heat flux due to wall slagging. Interestingly, large decreases in heat flux due to wall slagging are followed by large increases in heat flux as the magnetic field is turned on. As expected, the sidewall heat fluxes are not as affected by power "on" conditions as the anode and cathode. In general, the sidewall heat fluxes increase by about 15% for power "on" conditions. However, the right rear heat flux has been observed at times to increase by a more significant amount, in the range 30% to 40%. The right rear sidewall has also been observed to have significantly higher wear rates than the left wall. The exact cause of this nonuniformity is still under investigation.

8.1.2 Effect of Seed Addition on Channel Heat Fluxes

During the review of nominal channel heat fluxes described above, one of the observations made was that seed injection plays a role in slagging behavior during the initial portion of the test, particularly on the anode wall. During most MHD tests at the CDIF, seed flow is initiated within 5 minutes following main stage coal firing. Thus, it is usually difficult to separate the response to seed addition from the normal startup response. However, during one of the tests surveyed, 91-CC-1 on 11/13/90, seed flow was not initiated until approximately 40 minutes after main stage coal firing. Although the primary objective for this test was to help checkout the Avco/TDS current control circuits as anode current consolidators, the data is also valuable for evaluating the effect of seed addition on channel wall slagging behavior.

Figure 8-1 displays anode heat fluxes for the front and rear halves of the channel for the first 90 minutes of the test. Prior to turning the seed on, these heat fluxes are consistent with the nominal startup heat fluxes.
listed in Table 8-2. A rapid decrease in heat flux, particularly for the front anode, is observed as seed is turned on. After approximately 10 to 15 minutes, the heat fluxes for both the front and rear anode walls approach steady state values consistent with the values listed in Table 8-3. During the heat flux decay, periodic heat flux spikes are observed. These spikes can be characterized by a fast increase in heat flux believed to be due to slag breaking off the wall followed by a slower decrease due to reslagging of the wall. Similar heat flux spikes have been observed with precombustor components such as the precombustor combustion chamber and the transition section immediately downstream (Reference 8-1).

The cathode heat fluxes for the front and rear halves of the channel are shown in Figure 8-2. The cathode front heat flux was observed not to decrease significantly on addition of seed material. However, the similarity in cathode and anode heat flux values in the front of the channel for seed "on" conditions indicates that the cathode wall was already well slagged. The cathode heat flux in the rear of the channel also showed no response to seed. The cathode rear heat flux, however, was observed to decrease shortly after startup, to a value similar to the anode rear heat flux when seed was "on". This indicates that the rear cathode wall was slagging on its own without the aid of seed material.

Figures 8-3 and 8-4 show the heat fluxes for the left and right sidewalls in the front, middle, and rear of the channel. For all sidewall components, the heat flux response to seed was minor relative to the anode wall. However, significant heat flux spikes indicating stripping and rebuilding of the slag layer are evident in the rear of the channel, primarily on the left wall. Once seed flow was initiated, the frequency of these characteristic spikes decrease significantly. Also note that the steady state sidewall rear heat flux values were similar to the cathode and anode rear heat fluxes, indicating similar slagged wall conditions.

Thus, it appears evident from this test that both the front and rear anode walls do not slag well without the presence of seed in the channel. The front cathode wall appears to be already well-slagged, while the rear cathode wall is able to build a stable slag layer without the assistance of seed injection.
Figure 8-2. Cathode Wall Heat Flux Response to Seed Flow Initiation

Figure 8-3. Left Sidewall Heat Flux Response to Seed Flow Initiation
The slagging behavior of the sidewalls appear to follow that of the cathode rather than the anode, although there is some evidence of unstable slag layer formation in the rear of the channel prior to seed flow initiation.

More recently, additional seed-slag interaction tests have been conducted at the CDIF to provide further insight into the influence of seed on channel slagging behavior, as well as to evaluate combustor seed utilization and combustor second stage slagging behavior. The results of these tests are currently being analyzed and will be reported in future quarterly reports.

8.1.3 Individual Anode Coupon Heat Fluxes

Anode coupon heat fluxes are shown in Figure 8-5 for CDIF tests 91-CHEK-2, 91-MATL-4, and 91-MATL-5 conducted during January and February of 1991. The interelectrode boron nitride insulators upstream of anodes 34 and 35 were recessed 0.125 inch below the surface of the electrode in order to provide a groove for slag retention. On the other hand, insulators upstream of anodes 53 and 54 were installed such that they were flush with the electrode surface. Separate cooling circuits were plumbed to each group of electrodes to determine local heat fluxes.

Figure 8-5 shows a large drop off in heat flux for both sets of electrodes shortly after start up. Note that for these tests, the seed was turned on shortly after main combustor firing. The shaded region in Figure 8-5 spans the time in which seed flow is initiated. Based on the magnitude of the heat flux decrease (20 to 50%), it is apparent that both sets of anodes develop stable slag layers after 5 to 10 minutes. It is interesting to note that the characteristic heat flux spikes discussed above are only evident on the anode with nonrecessed insulators. This suggests that while both designs appear to slag well, anodes with nonrecessed insulators have more trouble during the initial slagging period due to the lack of a slagging groove.
Figure 8-5. Anode Coupon Heat Flux Results
The individual anode cooling circuits discussed above were retained for the more recent tests conducted at the CDIF. Analysis of this data is in progress and should provide additional insight into channel slagging behavior.

8.1.4 Summary/Conclusions

1) Channel heat flux distributions from recent CDIF tests were analyzed to determine the degree in which the channel walls are slagged during steady state combustor operation.

2) The anode walls do not appear to slag significantly prior to the initiation of seed flow. The cathode walls, on the other hand, appear to retain more slag from previous tests, and also tend to develop a stable slag layer without the assistance of seed. The slagging behavior of the channel sidewalls are closer to that of the cathode than the anode.

3) Selected anodes with and without recessed interelectrode insulators were instrumented with their own cooling circuits to determine slagging behavior. Both sets of anodes appeared to slag well as indicated by their heat flux response; however, anodes without recessed insulators appear to have more difficulty forming a stable slag layer initially due to the lack of a slagging groove.

8.2 ANALYSIS OF 1A1 SIDEWALL VOLTAGE MEASUREMENTS

8.2.1 Introduction

The purpose of this section is to present an analysis of sidewall voltage measurements taken during MHD testing in January and February, 1991 (91-CHEK-2 through 91-MATL-8). During these tests, a group of prototypical Z-wall sidewall elements were installed for design confirmation purposes. A total of 12 sidewall rows were installed in the 0.7-inch pitch region of the channel in the neighborhood of electrode 100. A schematic of the Z-wall configuration is shown in Figures 8-6A and 8-6B.

Most of the wear observed on segmented diagonal sidewalls has been attributed to two situations: 1) large gap voltages between two adjacent sidewall elements, and 2) large gap voltages between an electrode and a sidewall element. Figure 8-7 illustrates the highest wear regions on the 1A1 workhorse diagonal sidewalls. Large gap voltages between two adjacent sidewall elements in the core region are caused by a mismatch between the plasma equipotential angle and the wall angle. On the other hand, large gap voltages between the sidewall and the electrode wall appear to be primarily a function of boundary layer voltage drops, particularly at the anode wall. Large gap voltages may also exist between the sidewall and the cathode wall due to cathode wall nonuniformities.

As part of the Z-wall design confirmation tests, a large number of gap voltages were measured in the coupon region. The specific locations are indicated in Figures 8-8A and 8-8B. In addition, segments of the workhorse sidewalls were also instrumented with voltage transducers for comparison purposes. These include both 3-segment and 4-segment diagonal rows. A schematic of these gap voltage measurements is shown in Figures 8-8C and 8-8D.

8.2.2 General Observations

Approximately 20 power hours were accumulated from test 91-CHEK-2 through 91-MATL-8. The tests were conducted at the low-stress operating conditions with peak core current densities in the order of 0.8 amps/cm². Combustor operating conditions were 50 MWt, phi 1 = 0.55, phi 2 = 0.90, N/0 = 0.75 to 0.80, and 1.7% K. The channel operating parameters were 6000 volts, 1 to 1.2 MW, and 2.92 T.

Figures 8-9A through 8-9D are typical sidewall voltage plots of data taken during 91-CHEK-2, the first test of the series. The plots show the potential distribution along a row of sidewall elements. In each plot, the cathode voltage is used as the reference. Each bar on the plot represents a different sidewall element, starting at the cathode end bar and proceeding along the diagonal to the anode end bar. The anode voltage (relative to the cathode) is indicated by the solid point on the right axis. In general, a cathode end bar floats at a higher potential than its adjacent cathode, while the anode end bar floats at a lower potential than its adjacent anode. The intermediate diagonal elements typically float at potentials between these two extremes.
Figure 8-6A. Schematic of Right Z-Wall Configuration

Figure 8-6B. Schematic of Left Z-Wall Configuration
Figure 8-7. Observed Wear Patterns on the CDIF Sidewalls

Figure 8-8A. Sidewall Voltage Instrumentation - Z-Bar Right Sidewall
Figure 8-8B. Sidewall Voltage Instrumentation - Z-Bar Left Sidewall

Figure 8-8C. Sidewall Voltage Instrumentation - Forward Right Sidewall
The orientation of the sidewall potential distribution indicates that the plasma core equipotential angle (measured from the vertical) is slightly greater than the corresponding sidewall angle. Because of this, each sidewall gap in the core region must sustain a voltage of approximately 40 volts. A more detailed discussion of this topic is presented in Section 8.2.3.

Typical sidewall potential distribution plots for the workhorse straight bar elements are presented in Figures 8-9C and 8-9D. Note that the general orientation of these plots is the same as the Z-wall elements, again indicating that the core equipotential angle in these regions is also slightly greater than the wall angle.

During 91-CHEK-2, the largest Z-bar gap voltages were consistently measured between the anode end bar elements and their adjacent anodes. Typical measured values ranged from 70 to 100 volts. It should be noted that the gap voltage between an anode end bar element and the downstream anode, which was not instrumented during the tests, will be approximately 30 to 40 volts greater than this value, due to the increase in Hall voltage. A more detailed analysis of the sidewall-to-anode voltage differential is presented in Section 8.2.4.

8.2.3 Plasma Equipotential/Wall Angle Differences

The basic design philosophy of the Z-wall sidewalls is to align the wall segments with plasma equipotential lines in order to minimize gap voltages and related wear. Figure 8-10 shows the typical shape of the plasma equipotential line for a diagonal connection of N+12 with current controls. The angle between the core equipotential line and the vertical must be greater than the connection angle in order to compensate for boundary layer voltage drops. Figure 8-10A considers the case in which the diagonal wall angle matches the connection angle. Moving up along the diagonal row from the cathode wall, the adjacent plasma potential (relative to the cathode) is first positive, then negative, before returning to zero. Thus, different wall segments will float at different voltage potentials, resulting in gap voltage differentials.
Figure 8-9A. Typical Sidewall Voltage Distribution - Z-Wall
Figure 8-C. Typical Sidewall Voltage Distribution - 4-Segment Bar Wall
Figure 8-9D. Typical Sidewall Voltage Distribution - 3-Segment Bar Wall
A Z-wall, as shown in Figure 8-10B, allows one to decrease the mismatch between the core equipotential line and the wall by incorporating end segments normal to the electrode walls.

As mentioned previously, data from the CDIF Z-wall design confirmation tests indicates that the plasma equipotential angle is slightly greater than the wall angle. The average gap voltage in the core region between two diagonal wall segments is approximately 30 to 40 volts. This translates into an electric field of 400 to 500 V/m, or a 6 to 8 degree mismatch between the wall angle and the core plasma angle. Figure 8-11 shows a plot of electric field as a function of the difference in angles.

Mismatches between the core equipotential angle and the wall angle for the 1A4 channel are expected to be slightly less (approximately a 5 degree mismatch) as that observed during 1A1 coupon testing based on Avco/TDS calculations (Figure 8-12). In addition, the lengths of the 1A4 diagonal bar segments are shorter than the 1A1 coupons (7.1 versus 7.9 cm). This should further reduce the average gap voltages. All things considered, the 1A4 average gap voltages can be expected to be 10 to 20 volts less than those values observed with the 1A1 coupons. However, it should be noted that there is a considerable variation (both spatially and temporally) in the measured gap voltage data, with individual gap voltages measuring two times the average or more. In this regard, the 1A1 sidewall design confirmation tests provide a good indication of what to expect with the 1A4 sidewalls.

8.2.4 Sidewall-To-Anode Voltage Differentials

As mentioned previously, the highest sidewall gap voltages (70 to 120 volts) were measured between anode end bars and anode elements. Voltages between anode end bars and the downstream anode are 30 to 40 volts greater due to the increase in the Hall voltage. Previously with the workhorse diagonal walls, arc
Figure 8-11. Resultant Electric Field and Gap Voltage as a Function of Plasma and Wall Angle Differences

Figure 8-12. Comparison of 1A4 Sidewall Bar Angle with Calculated Plasma Equipotential Angle
damage at the sidewall-to-anode interface has been observed which appears to correlate with high sidewall-to-anode voltages. Because of the potential for catastrophic failure in this region, the sidewall-to-anode voltages were studied in more detail than the rest of the wall.

The cause of the high sidewall-to-anode voltages measured in the Z-wall test section, as well as on other sidewalls, appears to be related to the boundary layer voltage drop. Depending on the voltage profile through the boundary layer, the voltage difference between the anode end bar and the anode can have a value up to the total boundary layer voltage drop (typical range is 125 to 150 volts). Figure 8-13 illustrates this point. Assume that the anode end bar has the same height as the boundary layer. Three different voltage profiles are shown, each with a total boundary layer voltage drop equal to 150 volts. In each case, it is assumed that the anode end bar floats at the lowest adjacent plasma potential. This is a worse case assumption that has generally been supported by data from the Mark VII Z-bar testing, at least in the core region.

In case A, the voltage profile across the boundary layer is flat and equal to the anode potential. In this case, the voltage difference between the anode end bar and the anode would be approximately zero. In case B, the voltage profile through the boundary layer is fuller, dropping to -75 volts halfway through the boundary layer and then increasing back to zero at the wall. In this case, the sidewall-to-anode voltage would be -75 volts. In the last case, the entire boundary layer voltage drop occurs very near to the anode wall. Here, the sidewall-to-anode voltage would be -150 volts. Thus, the three different boundary layer voltage profiles yield significantly different sidewall-to-anode voltage differences.

It is interesting to note that all three types of boundary layer voltage profiles described above have been measured at the CDIF with an instrumented peg wall. Examples of each profile are shown in Figures 8-14A through 8-14C. In Figure 8-14A, there is virtually no difference in voltage between the anode and

![Figure 8-13. Effect of Boundary Layer Voltage Profile on Sidewall-to-Anode Voltage]
the first peg element. In addition, the voltage profile through the boundary layer is flat. In Figure 8-14B, the boundary layer profile resembles a Case B profile with a sidewall-to-anode voltage of approximately 70 volts. In Figure 8-14C, the boundary layer peg elements float well below the anode potential, with a sidewall-to-anode voltage of approximately 140 volts.

Based on the peg wall voltage data surveyed, it is not surprising that voltages as high as 130 volts were measured with the Z-wall configuration. In fact, for the tests between 90-MATL-1 and 91-MATL-3, the sidewall-to-anode voltage at electrode 71 was observed to be over 80 volts at least 92% of the time, and over 120 volts at least 25% of the time. On the other hand, there is also evidence of sidewall-to-electrode voltages consistently under 50 volts. During the same test period, the sidewall-to-electrode voltage at electrode 139 was below 50 volts 74% of the time, between 50 and 80 volts 25% of the time, and over 80 volts only 1% of the time.

The sidewall-to-anode voltages measured during the Z-wall confirmation tests are similar to the above mentioned pegwall data in that some sidewall-to-anode voltages remain high (over 80 volts) during the entire test while others tend to float at lower values. Examples of each type of behavior are shown in Figure 8-15.

Hence, while it appears that the sidewall-to-anode voltages are related to the shape of the boundary layer voltage profile, it is not known why there is a wide variation in shapes from one electrode to the next. At times the voltage drop appears to be dominated by an arc drop very near to the wall, while in other cases the voltage drop appears to be primarily due to diffuse current transport across the more resistive boundary layer. It is also interesting to note that specific sidewall-to-anode gaps tend to remain in the same regime (i.e. low or high voltage) for a number of tests, and also that low voltage gaps have been observed adjacent to high voltage gaps. What all this says is that there is still much to be learned about the factors which determine the size and character of anode voltage drops. Additional study in this area would be fruitful not
Figure 8-14B. Example of a "Case B" Boundary Layer Voltage Profile

Figure 8-14C. Example of a "Case C" Boundary Layer Voltage Profile
Figure 8-15. Example of Time History Plots for "High", Medium", and "Low" Sidewall-to-Anode Voltages
only for addressing sidewall-to-anode interface issues, but also for addressing channel performance scaling issues and anode lifetime issues.

In the next section, the results of two methods employed to reduce the sidewall-to-anode voltage difference will be discussed.

8.2.5 Effect of Sidewall Jumpers on Sidewall-to-Anode Voltage Differentials

Two different techniques have been used at the CDIF to reduce the sidewall-to-anode wall voltages. One is to jumper the last sidewall element to the upstream anode. This of course turns a portion of the sidewall into a current-carrying element. The other technique that has been tried is to jumper an anode end bar to an adjacent sidewall element that floats at a higher potential, in an attempt to lift up the lower potential element. The results of both of the efforts are discussed below.

The first technique was implemented along the rear sidewalls, which are composed of 3-segment straight diagonal elements. Anodes 142 through 182 were jumpered to their downstream sidewall elements as shown in Figure 8-16. The results of this technique were fairly dramatic. The high voltage between workhorse sidebars and the anode were significantly reduced (from 100 to 30-40 volts). In addition, no arc damage was observed in the jumpered region, while significant arc damage was observed both upstream and downstream. Finally, the jumpered sidewall elements did not show any increased wear which might be expected as a result of becoming an active current carrier.

The second technique, in which an anode end bar was jumpered to an adjacent diagonal element, is shown in Figure 8-17. This was implemented on the left Z-wall only between tests 91-MATL-4 and 91-MATL-5. Thus tests 91-CHEK-2 and 91-MATL-4 were conducted without jumpers, while 91-MATL-5 through 91-MATL-8 were conducted with jumpers. As shown in Table 8-5, the effect of the jumpers was

![Figure 8-16. Schematic of Sidewall Elements Jumpered to Their Upstream Anodes](image)
Figure 8-17. Location of Sidewall Jumpers Installed for Tests 91-MATL-5 Through 91-MATL-8

TABLE 8-5. COMPARISON OF AVERAGE SIDEWALL GAP VOLTAGE WITH AND WITHOUT JUMPERS INSTALLED

<table>
<thead>
<tr>
<th>Sidewall-to-Anode Voltages</th>
<th>No Jumpers*</th>
<th>Jumper on Left Wall**</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAB97-A109</td>
<td>96</td>
<td>62</td>
</tr>
<tr>
<td>LAB98-A110</td>
<td>97</td>
<td>32</td>
</tr>
<tr>
<td>LAB99-A111</td>
<td>74</td>
<td>56</td>
</tr>
<tr>
<td>LAB100-A112</td>
<td>26</td>
<td>41</td>
</tr>
<tr>
<td>RAB97-A109</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>RAB98-A110</td>
<td>97</td>
<td>93</td>
</tr>
<tr>
<td>RAB99-A111</td>
<td>67</td>
<td>56</td>
</tr>
<tr>
<td>RAB100-A112</td>
<td>94</td>
<td>84</td>
</tr>
<tr>
<td><strong>Middle Bar-to-Anode Middle Bar Voltage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LMB98-LAMB97</td>
<td>70</td>
<td>111</td>
</tr>
<tr>
<td>LMB99-LAMB98</td>
<td>62</td>
<td>68</td>
</tr>
<tr>
<td>LMB100-LAMB99</td>
<td>72</td>
<td>97</td>
</tr>
<tr>
<td>RMB98-RAMB97</td>
<td>68</td>
<td>53</td>
</tr>
<tr>
<td>RMB99-RAMB98</td>
<td>74</td>
<td>68</td>
</tr>
<tr>
<td>RMB100-RAMB99</td>
<td>81</td>
<td>52</td>
</tr>
</tbody>
</table>

*Tests 91-CHEK-2, 91-MATL-4
**Tests 91-MATL-5 through 91-MATL-8
to lower the sidewall-to-anode voltages in three of the four cases. Reduction in average gap voltages varied from 18 to 62 volts. In the fourth case, the average gap voltage increased from 26 to 41 volts. This gap voltage, however, was originally quite low relative to the other three on the left wall and all four on the right wall.

A second effect of the jumpers was to increase gap voltages on other regions of the wall, particularly the gap voltage between middle bar and upstream anode middle bars (see Figure 8-17). In two of the three cases, these gap voltages increased from an average of 70 volts to the 100 to 110 volt level. In the third case, the gap voltage did not change significantly. The increases in this gap voltage are attributed to the fact that when the two sidewall elements were jumpered together, the group tended to float at a potential somewhere between the potentials of the two elements prior to being jumpered. Hence, the lower potential anode end bar increased in voltage while the higher potential anode middle bar decreased in voltage. The latter response in turn increases the gap voltage between the anode middle bar and the middle bar. Thus, the net effect of the jumper is to shift the high voltage gap away from the anode wall and into the diagonal wall section. This trade-off may prove worthwhile in the long run since higher sidewall-to-anode voltage differences carry with them a greater risk of catastrophic failure since strong arcs are driven into the anode wall by Lorentz forces.

One interesting item of note is that the response of the sidewall wall elements to jumpers is somewhat inconsistent with the notion that a sidewall element will tend to float at the lowest plasma potential. If this were universally true, then the potential of the anode middle bar would have decreased to the level of the anode end bar. However, the two connected elements tended to float at some average potential. This implies that there may be some secondary factors, i.e. slag layer current leakage, arcing, at work that must also be considered.

Of the two methods employed to reduce sidewall-to-anode voltages, the first method, in which the sidewall element is jumpered to the upstream anode, appears to be more effective. Dramatic reductions were observed both in the sidewall-to-anode voltage as well as the degree of arc damage in this region. This configuration should continue to be tested in order to determine the level of current collected by the sidewall elements as well as to identify any increased wear areas. The second method, in which adjacent sidewall elements are connected, also appears to have some positive benefit. Additional testing is required, however, to confirm previous results.

8.2.6 Summary/Conclusions

1) The orientation of the Z-wall potential distribution indicates that the plasma core equipotential angle is slightly greater than the corresponding sidewall angle (approximately 6 to 8 degrees). This results in an average gap voltage of 40 volts in the core region.

2) Average sidewall gap voltages for the 1A4 channel are expected to be slightly less (by 10 to 20 volts) due to a smaller difference in plasma and wall angles as well as a shorter sidewall bar length (7.1 versus 7.9 cm).

3) The largest sidewall gap voltages were measured at the sidewall-to-anode interface (70 to 100 volts). These high voltages are consistent with previous sidewall-to-anode voltage measurements on the 1A1 forward peg wall, as well as measurements on the 3-segment diagonal sidewalls.

4) The sidewall-to-anode voltages appear to be related to the shape of the boundary layer voltage profile. Large sidewall-to-anode voltages correspond with large voltage drops very near to the anode wall (i.e. an arc voltage drop).

5) To date, the most successful way to reduce high sidewall-to-anode voltage differences is to jumper a sidewall element to the anode located one electrode upstream. For the 1A1 channel, this technique reduced the sidewall-to-anode voltages from 90 to 30 volts and appears to prevent arc damage at the sidewall-to-anode interface. More testing is recommended in order to fully evaluate this technique.
6) A second technique, in which an anode end bar is jumpered to an anode middle bar, also appears to reduce sidewall-to-anode voltages by relocating the high voltage gap to the anode middle bar/middle bar gap. Here, the trade-off appears to be between reducing the risk of catastrophic failure from sidewall-to-anode arcs and higher wear rates at the anode middle bar/middle bar gap.

8.3 MARK VII INVESTIGATION FOR THE 1A4 SEGMENTED DIFFUSER

8.3.1 Summary

The segmented forward supersonic section of the diffuser on the 1A4 channel will be located in the magnet fringe field and will thus vary from about 0.75 T at the upstream end to less than 0.1 T at the downstream end of the section. With this magnetic field profile, the diffuser section will behave like a Faraday generator at open circuit conditions and will develop a potential across it. If the "interanode" voltages become too high (especially near the interfaces between the unloaded segments and either the current controls or the rear diffuser sections), breakdown will occur and damage the forward supersonic section. In addition, since the rear diffuser sections are grounded and the positive inverter buss will be tied to ground through a resistor to keep the channel from floating at a high potential, there is the possibility that a ground loop will develop and produce unacceptably high leakage currents.

To predict the electrical behavior of the unloaded diffuser segments, an analytical model was developed for a generic unloaded region at the back of an MHD channel. The trends predicted by the model were checked against data obtained from a 1A1 test at the CDIF where the last 11 anodes were left floating.

Once the trends had been verified, an investigation was carried out on the Mark VII workhorse channel to examine the effect of various bleed resistor profiles on an unloaded rear section of the channel. This provided important qualitative trends which will guide the selection of any necessary bleed resistors at the CDIF. A future test is planned on the 1A1 channel with the rear 8 electrodes left unloaded to simulate the segmented diffuser under more realistic operating conditions. The data obtained from both the Mark VII and 1A1 tests will be used to refine the analytical model for the 1A4 diffuser.

8.3.2 Analytical Model of Unloaded Rear Channel Section

8.3.2.1 Introduction

In order to determine the potential developed across an unloaded rear channel section (or a segmented forward supersonic diffuser section), a 2-D analytical model was set up to calculate current circulation in the section. The section is split into a finite number of segments, and the electrical properties are modeled at each segment simultaneously. Boundary conditions are applied and a set of coupled linear equations are developed to solve for the unknown currents. Voltages are back-calculated from these currents. Bleed resistors can be added to investigate the appropriate way to configure the unloaded section to limit any adverse potentials on the anode wall.

8.3.2.2 General Model

Figure 8-18 shows a schematic of a generic segment, which consists of nodes i and i+1. The model includes the boundary layers and electrically conductive slag layers as well as the plasma. The voltage sources included in the model represent the Faraday and Hall voltages developed by the plasma, since both the diffuser and rear channel sections are inside the magnet field.

The currents I_5 and I_F are the transverse currents through the boundary layers and plasma, respectively. The subscripts t and b refer to top and bottom of the channel. The Hall currents I_H run axially through both the boundary layers and the core, while the current leakage through the slag layer is given by I_s. The core, boundary layer, and slag layer resistivities are given by R_F, R_H, R_t, R_b, and R_s. Note that the Faraday resistance is assumed to be divided equally in the two core transverse regions. Similarly, the Faraday voltage V_F is split evenly. The other voltages, V_H, are the Hall voltages in the boundary layers and the core.
From this model, a series of equations can be developed for the voltages and currents at each segment (nodes i and i+1). The voltages will be expressed in terms of the currents, and then voltage conservation around each loop will be used to solve for the currents. By back-substitution, the voltages can then be found. Note that by current conservation, some of the currents can be eliminated, so that the final matrix of equations to be solved will depend only on the axial currents $I_{si}, I_{Hi}, I_H,$ and $I_{Hi+1}.$

For initial application of the model, several simplifying assumptions were made. First, the boundary layer conductivity is assumed to be $1/2$ the core conductivity. Also, since the length of the section being analyzed is short, the electrode width, Hall parameter, and conductivity are assumed constant over its length. The voltages are assumed to be a function of an average of the four currents which surround them. With four unknown currents to solve for at each node, and $n+1$ nodes where $n$ is the number of segments, a matrix equation can be developed which has the form:

$$[M][I] = [V]$$

where $M$ is a $4n \times 4n$ constant coefficient matrix, $I$ is a $1 \times 4n$ column of unknown currents at each node, and $V$ is the $1 \times 4n$ column of known voltages generated by the core uBH. The matrix $M$ can be expressed as a diagonal matrix of three submatrices $A$, $B$, and $C$. Each is a $4 \times 4$ matrix of coefficients that relates the voltages at that node to the axial currents. The submatrix $A$ incorporates the contribution of the upstream currents, $B$ is for the currents at that particular node, and $C$ is for the downstream currents. At both the first and last nodes, special boundary conditions apply. The column matrix $V$ contains any known variables, such as these boundary conditions, along with the uBH term.
8.3.2.3 Model Applied to the 1A1 Rear PTO Section

The above discussion is for a generic unloaded section of the channel, but the model will now be specifically described for the case where node 1 is the last diagonally connected anode and consolidated cathode, and node n+1 is the interface between the unloaded segments and the diffuser. Eight unloaded segments are assumed, since this will be the configuration tested at the CDIF in September 1991.

For this configuration, known current inputs will be applied to the model at the first node. These include an electrode current from the anode (I\(_A\)), two axial boundary layer currents (I\(_B\)), and one axial core current (I\(_C\)). The values for these currents are obtained from a representative MHD4 calculation. The current leaving the first node through the current control (or consolidation resistor), I\(_{CC}\), sums together with the currents from all of the other consolidated cathodes, I\(_{Buss}\), to produce a load current I\(_{LD}\). The load current, in turn, is reduced by the amount of current, I\(_G\), which leaks out from the inverter buss to ground through the buss resistor. In the case of either resistive consolidation or current controls, both I\(_{CC}\) and I\(_{Buss}\) are fixed as a percentage of (I\(_{LD}\) + I\(_G\)). With resistors, these percentages are determined by the axial electric field across the PTO. With current controls, these ratios are determined by the current control turns ratios. In either case, only I\(_{LD}\) must be known.

There are now two additional voltage loops to consider: 1) the first from ground through the inverter buss and the cathode slag layer back down to ground through the last cathode, and 2) the second from ground through the last anode down through the plasma to the last cathode and back to ground. A third equation arises from current conservation around the entire control volume, including the leakage currents. In order to solve the matrix equations, the [M] and [V] matrices must be modified to include the additional ground loop equations. With the additional equations and unknowns, [M] has three extra rows, and three more columns must be added on:

\[
[M_2] = \begin{bmatrix}
D & \vdots & M & \vdots & E & \vdots & G
\end{bmatrix}
\]

The original matrix [M], consisting of submatrices A, B, C, and zeros, is still preserved in [M\(_2\)], which is a (4n+3) x (4n+3) matrix. The submatrices D, E, and F are all (4 x 3) and are added on to account for the additional unknown variables in the original equations. G is the ((4n+3) x 3) matrix of the new ground loop equations. The whole matrix [M\(_2\)] gets multiplied by the matrix of currents [I\(_2\)] to produce the voltage matrix [V\(_2\)]. Now, though, [I\(_2\)] is a ((4n+3) x 1) column matrix which adds in IGA, IGC, and IG at the bottom of the original column. Similarly, [V\(_2\)] must have three new rows added on at the end. Also, since the first and last nodes now have boundary conditions which carry over into the other nodes, the submatrices in [V] must be modified.

8.3.2.4 Solution of 1A1 Unloaded Rear Section Using the Model

Now that the model has been developed, values may be given for all of the resistors, currents, and voltages which are input as knowns. From the MHD4 analytical data match of CDIF test 89-DIAG-11 at the peak power condition of 5000 V load voltage, the following values were obtained:
To determine \( R_{CC} \) (the equivalent resistance across the last current control), the potential where the buss floats must be found. The schematic shown in Figure 8-19 illustrates how the potentials are defined. The \( \Delta V \) terms represent the bucking or boosting that the current controls provide at each cathode to even out the currents. The inverter buss will float approximately where the \( \Delta V \)'s balance out to zero. Thus from the data match of 89-DIAG-11 at the nominal load condition, \( \Delta V \) for the last current control was found to be 2.97 V. Now the impedance \( Z \), which arises from the time-dependent current through the current controls, must be calculated to find the total potential from the cathode to the inverter buss. There are three terms in the impedance which arise from: 1) the resistances across the diodes and GTO's, 2) the self-inductance of the slave transformer, and 3) the mutual inductance of the slave transformer with respect to the time-varying master current. Therefore in each branch of the current control:

\[
I_{cc}Z = R_{GTO}I_{cc} + L \frac{dl_{cc}}{dt} - M \frac{dI_{M}}{dt}
\]  

(8-3)

where \( R_{GTO} \) is the switching resistance, \( L \) is the self-inductance, \( M \) is the mutual inductance, and \( I_{M} \) is the current through the master side of the transformer. For this analysis, only a very rough approximation is made for the time-varying elements. It is assumed that during one half of the cycle, \( R_{GTO} \) on one side is zero and \( dl_{cc}/dt \) on that side is \( I_{cc}/2 \), where \( n \) is the switching frequency. Assuming that the turns ratio is 1, it can be approximated that \( dI_{M}/dt \) is the same as \( dl_{cc}/dt \). The other side does not contribute because the GTO on that side is open. Using the following values for the constants (Reference 8-2):

\[
L = 0.061 \text{ Henrys}
\]
\[
M = 0.06098 \text{ Henrys}
\]
\[
n = 1 \text{ kHz}
\]

with a load current of 208 A and zero leakage leads to an estimate of \( Z = 0.04 \) ohms. Since:

\[
R_{CC} = \frac{\Delta V + I_{cc}Z}{I_{cc}}
\]  

(8-4)
$R_{cc}$ is about 0.27 ohms when $I_{cc}$ is approximately 13 A. Inserting this value of $R_{cc}$ into the matrices produces the interelectrode voltages shown in Figure 8-20. Note that there are large interface voltages between the last electrodes and the diffuser, and that the buss floats about 190 volts from ground.

As a check, the results of this analysis can be compared to the data from 89-DIAG-9, in which the last 11 anodes were left floating. Figure 8-21 shows a schematic of the rear PTO during this test. There are key differences between this test configuration and the analytical model: in 89-DIAG-9 there are no floating cathodes, there is iron oxide injection on the cathode wall, and the last consolidated cathode is connected directly to ground. In addition, there are no bleed resistors, although the slag itself still provides some leakage path to ground. With this cathode configuration, the only comparison that can be made is the interanode voltages. Despite the differences between the test configuration and the model, though, the model does capture the salient features of the voltage pattern in an unloaded anode section as shown in Figure 8-22.

8.3.3 Mark VII Investigation of Unloaded Rear Channel Section

8.3.3.1 Introduction

A pair of tests were carried out on the Mark VII to experimentally determine the effect of various bleed resistor profiles on the gap voltages developed between unloaded channel segments. The tests were performed both under barewall and slagged conditions. No iron oxide was injected during the slagging operation because it had not appeared to reduce the cathode shorting in past tests. The results of these tests provided both qualitative trends and data to input to the analytical model.

8.3.3.2 Test Configuration

The investigation was performed using the Mark VII workhorse channel, wired with an external overlap of 9 electrodes. The rear power takeoff was moved upstream 16 electrodes. This brought the first
Figure 8-20. Calculated Potentials on the 1A1 Channel with the Last Eight Electrodes Floating

TEST: 89-11AG-9

NOTE: ALL SIDEBARS DISCONNECTED.
: ALL CC CIRCUITS ARE SET TO 3/3 TURNS RATIO.

Figure 8-21. Test Configuration of the 1A1 Rear PTO Region with the Last Eleven Anodes Floating
unloaded electrode to a magnetic field of about 1.9 T. The unloaded interelectrodes consisted of No. 50 through No. 65. Anode and cathode No. 66 were shorted to the diffuser to ground them. Bleed resistors were provided between all interelectrode gaps, and the voltages were measured across each. The load cart was used for the bleed resistor network so that the values of each resistor could be varied. The voltage between the positive cathode buss and ground was measured, and during the slagging test, a resistor was added to provide a leakage path for the buss. Figure 8-23 shows a schematic of the channel during these tests.

The channel was operated at nominal conditions: B field = 2.5 T, φ = 1, N/O = 0.7, and seed fraction = 1% K. When it was running with slag, the ash carryover was approximately 30%. The nominal diagonal load was 15 ohms, but load sweeps were conducted at several points in both tests. The barewall case was run April 20, 1991 and the slugged test was run April 26, 1991.

8.3.3.3 Test Results: Barewall

During this test, the bleed resistor network was initially set so that all gap resistances were open to identify the worst case gap voltages. The only leakage present in this configuration presumably was through the molten potassium (seed) on the walls. The resulting interelectrode voltages are shown in Figure 8-24. IAV No. 49 is the interface between the last diagonally loaded anode and the first unloaded one. The interaction between the unloaded anode and anode 49, where a large transverse current is forced by its current control, produces the large negative voltage spike. A similarly large positive voltage spike appears at the interface between anodes Nos. 65 and 66, since No. 66 is effectively grounded. On the cathode wall, these spikes reverse polarity.

Attempts were made to mitigate the large gap voltages by changing the bleed resistor network. Figures 8-25(a) and 8-25(b) show the gap voltages for the final resistor profile at open circuit and short circuit conditions. As an approximation to the upcoming slagging test, the bleed resistors were then all set

![Figure 8-22. Comparison of Analytical Model to CDIF 1A1 Data](image-url)
to 2 ohms to simulate the slag layer leakage and another load sweep was conducted. No spikes appeared on either the anode or cathode walls.

8.3.3.4 Test Results: Slagged

Once again, the initial bleed resistor network was set so that all gap resistances were open. The test was started with the cathode buss connected to ground through a 10-ohm resistor. A load sweep was conducted in this configuration, and it was observed that there were still spikes at the cathode diffuser interface and the anode current control interface. In addition, intermittent voltage spikes of up to 40 volts were recorded at anode No. 58. This was assumed to be related to localized, intermittent spalling/redevelopment of the slag layer. Figure 8-26 shows the interelectrode voltages at matched load conditions.

The buss resistor was then removed and the channel was operated at the matched load (15 ohms). The buss-to-ground voltage increased by about 10 volts. A bleed resistor ramp from 2 to 8 ohms was next added on both the anode and cathode diffuser interfaces. There was no effect (i.e., the voltage spike remained), presumably because the slag layer resistance was lower than the smallest bleed resistor and thus the leakage would not preferentially go through the resistors. As a comparison to the barewall case, the bleed resistors were then all set to 2 ohms and a load sweep was conducted. As expected, the gap voltage profiles were uniform and the buss-to-ground voltages were the same as they were for the barewall run. Finally, a 2-ohm resistor was connected between the buss and ground, and the diagonal load resistance was set to 15 ohms. The buss-to-ground voltage was reduced to 8 volts, with a leakage current of 4 amps.

8.3.3.5 Comparison of Experimental Data with Analytical Predictions

Using first the barewall case with all bleed resistors open, the measured gap voltages at matched load were compared with those predicted by the analytical model to verify the model results. The rear unloaded section of the channel was represented, for simplicity, as 8 segments where each segment was two
Figure 8-24. Interelectrode Voltages on the Mark VII: Barewall, Matched Load, Ali Bleed Resistors Open
Figure 8-25(a). Interelectrode Voltages on the Mark VII: Barewall, Open Circuit, Ramped Bleed Resistor Profile
Figure 8-25(b). Interelectrode Voltages on the Mark VII: Barewall, Short Circuit, Ramped Bleed Resistor Profile
Figure 8-26. Interelectrode Voltages on the Mark VII: Slagged, Matched Load, All Bleed Resistors Open
electrodes wide. Thus the pitch of the segments was 1.4 inches. From a Mark VII MHD4 data match and from interelectrode gap resistance measurements, (Reference 8-3), the following values were assumed:

<table>
<thead>
<tr>
<th>Node</th>
<th>uBH/2 (V)</th>
<th>Rδ= 12.1 ohms</th>
<th>Rs = 12 ohms</th>
<th>Rl = Rb = 2.2 ohms</th>
<th>Rf = 4.2 ohms</th>
<th>RH = 0.4 ohms</th>
<th>ILD = 61 A</th>
<th>IA = 8.4 A</th>
<th>IBL = 0 A</th>
<th>IC = 1.3 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>276.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>260.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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In addition, the buss resistor RBuss was set to $1 \times 10^{10}$ to simulate an open connection to ground. Inserting these values into the matrix equation and solving for the unknown currents produced the interelectrode voltages shown in Figure 8-27. Also shown in this figure are the actual measured gap voltages. Note that the experimental values are the sum of two adjacent gaps since the analytical pitch was two electrodes wide. It can be seen that the model predicts the trends of the gap voltages relatively well, although it needs some adjustment at the boundaries.

In the upcoming quarter, the model will be fine tuned by more rigorous treatment of the boundary layer conductivity, the use of measured conductivity, and calculated Hall parameter profiles and comparing the results with other operating conditions from the Mark VII tests.

REFERENCES FOR SECTION 8


Figure 8-27. Comparison of Analytical and Measured Gap Voltages on the Mark VII Floating Electrodes under Barewall Conditions and Open Bleed Resistors
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 Executive Committee of the TTIRC was held on February 21, 1991 at the Pittsburgh Westin William Penn Hotel in conjunction with the annual DOE MHD Contractors' Review Meeting. Business included updates from the three POC programs with a special emphasis on test plan consistency, seed regeneration economics and Western coal options, status of the Clean Coal Technology proposal, and DOE action regarding POC task force program recommendations.

The fifth semi-annual status report of the MHD TTIRC was approved for final distribution. A draft of the sixth semi-annual status report (October 90 through March 91) is currently being prepared. Distribution to the DOE and TTIRC Executive Committee for review is scheduled for May.

The annual meeting of the General Committee is scheduled for a half day session on June 17, 1991 at the OMNI Royal Orleans Hotel in New Orleans. The meeting precedes the 29th Symposium on Engineering Aspects of Magnetohydrodynamics (SEAM).
10. PLANNED ACTIVITIES

Task 1
- Release the Channel Requirements Document.
- Release the Test Plan update for final review.
- Attendance of the SEAM 29 conference by selected program personnel.
- Maintain the detailed integrated schedule for the manufacturing phase of the program.
- Continue to analyze and model combustor performance in terms of slag recovery and seed utilization and provide recommendations for future tests at the CDIF.
- Continue to study precombustor slagging behavior.
- Evaluate slag tank operation and provide recommendations on system modifications.

Task 2
- Complete purchase order placement and review of manufacturing planning documents. Manufacturing will be in progress.
- Complete fabrication of pressure shells, second stage, slagging stage baffle, PC combustion can, and endplate cooling panels.
- Complete preparation for assembly of the prototypical combustor at TRW.
- Complete the Low Pressure Cooling System (LPCS) design and initiate manufacturing.

Task 3
- Receive material and initiate fabrication of sidewall elements.
- Complete assembly of channel mock-up and document external packaging details.
- Complete design of channel inlet frame.

Task 4
- Rework diffuser to add studs for electrical connections.

Task 5
- Continue construction of the switch modules and the filter networks that makeup the consolidation circuits.
- Test the completed consolidation circuits.

Task 6
- Checkout Phase II of the slag rejector installation. (Due to mid-May shutdown required for data acquisition system (DAS) installation, only two weeks of checkout and testing will be available.)
- During the planned shutdown, the following will be installed:
  - DAS (data acquisition system)
  - 50-hour oxygen system upgrade
  - Slag removal system (Phase III)
  - Westinghouse anode current consolidation cabinet
- The following activities related to workhorse hardware will be performed:
  - Install improved workhorse sidewall elements
  - Replace OFV burner, chamber and elbow assemblies
- Install rectangular second stage
- Remove and evaluate "coupon" filler

Task 8

- Hold TTIRC General Committee meeting in June 1991, in conjunction with the 29th Symposium on Engineering Aspects of Magnetohydrodynamics (SEAM) in New Orleans.
- Prepare draft copy of sixth semi-annual status report for distribution to the DOE and TTIRC Executive Committee for review.
11. SUMMARY

Based on hardware inspection and acid corrosion test results, a 110°F cooling water temperature (with 200°F dryout capabilities) was selected for the Low Pressure Cooling System (LPCS). Design modifications were incorporated to protect the non-gas facing surface of the components from low temperature corrosion.

Purchase orders were placed for the combustor cooling panels, slagging stage baffle, and pressure shells. Second stage hardware manufacturing is in progress. Negotiations for the design and fabrication of the LPCS were completed. Fabrication of the Current Consolidation Subsystem was initiated.

Final design of an MHD channel for POC testing has been completed. The channel was designed to be capable of 1.5 MW_e power output and a lifetime of 2000 hours. Emphasis was placed upon durability and reliability. Hence, specific measures were taken to design against channel damage due to electric faults. The life-limiting issues associated with electrochemical corrosion and erosion of gas-side surfaces were addressed by the use of various materials with proven wear characteristics in a coal-fired MHD channel environment. Work was conducted to identify and rectify potential problem areas in the channel design including: 1) leaky water tubes, 2) pitting on sidewall coupons, and 3) water-side corrosion.

Test activities at the CDIF were divided into two distinct test series: 1) accumulation of electrical hours on the prototypical channel elements which had been installed in the workhorse 1A1 channel, and 2) checkout of the continuous slag rejection system. A total of 5.2 thermal hours and 2.5 electrical hours were accumulated. Installation of Phase II of the slag rejector system was completed.

In the Combustion Subsystem, efforts continued to focus on understanding and improving the current levels of slag recovery and seed utilization achieved by the combustor. Channel data analysis activities continued in support of prototypical coupon testing at the CDIF. To predict the electrical behavior of the unloaded diffuser segments, an analytical model was developed for a generic unloaded region at the back of an MHD channel.
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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 Table 7-1. A comprehensive discussion describing modifications to the test train and the facility is detailed in Section 7.2.

A.1 LONG DURATION TEST SUMMARIES: 1991-COUPON CHANNEL BUILD NO. 1

A.1.1 91-MATL-07 through 91-MATL-08 - Objectives (Refer to Table 7-2)

The objectives of this test series were: 1) to provide 50 electrical hours on the coupon channel at prototypical electrical stress conditions (Reference Operating Condition No. 2, N/O = 0.76), and 2) to obtain as long of a duration test as possible (16 to 24 continuous power hours) in order to evaluate the long term effects of iron oxide injection.

A.1.2 91-MATL-07 - Results - Power Time = 15 Minutes (02/05/91)

The test was terminated due to a meter panel in the central control room arcing and smoking. This occurred during the initial startup of power generation when the inverter reference voltage was increased to 6 kV. The arc occurred in a wire bundle (located under the diffuser) that was connected to the aft right sidewall voltage measurements as well as to the meters in the control room. The arc occurred in an area where one conductor was connected to A276 (at ~200V potential) and passed next to another conductor connected to the aft sidewall voltage sensor (=A177) which is at a much higher voltage. An investigation by MSE stated that the problem was due to a crimp connection on the conductors which was faulty. There were no signs of arc activity on the charmel or on the grounded stand at the diffuser.

A.1.3 91-MATL-08 - Results - Power Time = 2 Hours 16 Minutes (02/07/91)

The test was incomplete and had frequent starts and stops. Problems during the test were as follows:

1) Frequent coal flow plugging was the cause of the three shutdowns.
2) The test was ultimately terminated due to the discovery of a water leak on the magnet which originated from the internal windings.
3) The No. 1 iron oxide slurry pump plugged and could not be restarted - cathode wall nonuniformities increased substantially.

Post-test observations revealed:

1) Diodes in one of the current control slave units (slave No. 14 of cabinet No. 8) had failed.
2) CFPC coal flow pinch valve was plugged with coal and the entire line upstream of the valve had plugged.
3) Minor cooling water leak on the headend plate of the slagging stage in the same location as a previous weld repair.

A.2 SLAG REJECTOR SYSTEM TEST SUMMARY

A.2.1 91-SREJ-01 - Objectives (Refer to Table 7-3)

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.2.2 91-SREJ-01 - Results - Thermal Time = 1 Hour 36 Minutes (04/29/91)

1) The facility started up surprisingly well after being down so long.
2) The slag rejector auto cycle stopped at the denseveyor water refill cycle due to flow switch fluctuations. This will be mitigated by installing a time delay in the sequence.
## APPENDIX B. 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. $\beta$ - Beta - Hall parameter
21. $\delta$ - Boundary layer thickness (Meters)
22. $\sigma$ - 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, $\sigma$ 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. $\phi_0$ - Precombustor Equivalence Ratio - Ratio of oxygen input to the coal-fired precombustor combustion chamber to stiochiometric oxygen required for complete combustion of fuels.
24. $\phi_1$ - First Stage Equivalence Ratio - Ratio of oxygen input to the first stage to stoichiometric oxygen required for complete combustion of fuels.

25. $\phi_2$ - 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/cm$^2$)

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. $M_{We}$ - Electric megawatts (power output)

37. $M_{Wt}$ - 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. $P_e$ - 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. $\Delta V$ - Transverse voltage drop (e.g., $\Delta V_{bl}$ - across boundary layer) (volts)

Definitions

49. Heat Flux - Heat loss per unit area (watts/cm$^2$).

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, SO$_3$ -free ash fed to the combustor (SO$_3$ is volatile and is not found in the slag).

52. Weight Percent Oxygen in First Stage (wt. % O$_2$) - Weight percent of oxygen in vitiated gases entering combustor first stage.
END

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8/25/92