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MHD GENERATOR ELECTRODE DEVELOPMENT

Quarterly Report for Period October–December 31, 1980

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January 1981

Work Performed Under Contract No. AC01-79ET15529

Westinghouse Electric Corporation
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Pittsburgh, Pennsylvania

U. S. DEPARTMENT OF ENERGY

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JANUARY 1981

PREPARED FOR THE
UNITED STATES DEPARTMENT OF ENERGY

Under Contract No. DE-AC-01-79-ET-15529

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TABLE OF CONTENTS

	<u>Page</u>
I. ABSTRACT	1
II. OBJECTIVE AND SCOPE OF WORK	2
WBS 1.1 - ELECTRODE/INSULATOR MATERIALS	3
WBS 1.2 - ENGINEERING TESTS	3
WBS 1.3 - WESTF OPERATIONS	5
WBS 1.4 - WESTF GENERATOR CORRELATION	6
WBS 1.5 - PROJECT MANAGEMENT	6
III. SUMMARY OF PROGRESS TO DATE	7
1.0 WBS 1.1 - ELECTRODE AND INSULATOR MATERIALS	9
2.0 WBS 1.2 - ENGINEERING TESTS	12
3.0 WBS 1.3 - WESTF OPERATIONS	13
4.0 WBS 1.4 - WESTF-GENERATOR CORRELATION	13
5.0 WBS 1.5 - PROJECT MANAGEMENT	15
IV. DETAILED DESCRIPTION OF TECHNICAL PROGRESS	16
1.0 WBS 1.1 - ELECTRODE AND INSULATOR MATERIALS	16
1.1 WBS 1.1.1 - Materials Research	16
1.2 WBS 1.1.2 - Laboratory Screening Tests	20
1.2.1 Electrochemical Corrosion Tests	20
1.2.2 Anode Arc Erosion Tests	35
1.3 WBS 1.1.3 - Fabrication Development	38
2.0 WBS 1.2 - ENGINEERING TESTS	40
2.1 WBS 1.2.1 - Test Engineering	40
2.1.1 Development Requirements	40
2.1.2 Experiment Design	43
2.1.3 Post-Test Analysis	66
2.2 WBS 1.2.2 - Test Assembly Fabrication	66
3.0 WBS 1.3 - WESTF OPERATIONS	70

TABLE OF CONTENTS (Continued)

	<u>Page</u>
4.0 WBS 1.4 - WESTF/GENERATOR CORRELATION	79
5.0 WBS 1.5 - PROJECT MANAGEMENT	80
V. SUMMARY PLANS NEXT REPORTING PERIOD	81
VI. CONCLUSIONS	83
VII. REFERENCES	84

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
1	Work Breakdown Structure	4
2	Laboratory Screening Test Summary	11
3	Summary of Planned WESTF Tests	14
4	Commercial Alloy Test Summary	19
5	Advanced Metals and Non-Metals Compositions	21
6	Electrochemical Corrosion Rates of Metal Alloys in Potassium Sulfate Electrolytes	26
7	Summary of Planned WESTF Tests	41
8	Thermal Characteristics of Hot MTS Test Section	45
9	Original Test Conditions, WESTF Tests 52 and 54	51
10	Revised Test Conditions, WESTF Tests 52 and 54	52
11	Electrode Sizes, WESTF Tests 52 and 54	54
12	Coolant Circuit Flow Data, WESTF Test 50	68

LIST OF FIGURES

Figure No.	Title	Page
1	Program Schedule and Status	8
2	Schematic of Arc Impingement on Slag Covered Alloy Anode	17
3	Weight Loss of KHSO_4 versus Temperature in Nitrogen Atmosphere	23
4	Schematic of Electrochemical Corrosion Test	25
5	Comparison of Electrolytic Anode Corrosion in Aqueous K_2SO_4 with Faradaic Loss	28
6	Anode-Cathode Voltage Drops for Several Stainless Steel Alloys as a Function of Test Duration in Molten KHSO_4 at 300°C	30
7	Electrochemical Corrosion Rates of Fe-Ni-Cr Alloys (where $\text{Cr} \approx 18-30\%$) in Molten KHSO_4 as a Function of Alloy Nickel	31
8	Correlation Between Electrochemical Test and Mark VII (AVCO) MHD Generator Tests	32
9	Electrolytic Corrosion of Various Metals in Molten Potassium Sulfate Compounds	34
10	Schematic of Anode Arc Test	37
11	Anode Arc Erosion of Several Alloys (KHSO_4 Corrodent)	39
12	MTS Test Section - Hot Version	44
13	MTS Coolant Channel Schematic	47
14	Effect of 0.060 Inch Clad on Surface Temperature of Copper Electrode, Equilibrium Slagging Conditions	49
15	Electrode Configuration, WESTF Tests 52 and 54	53
16	WESTF Test Section Design Changes	56
17	Tubing Connections, WESTF Test Section	58
18	WESTF Test Section Configuration	60
19	Components of WESTF Peg Wall Assembly	61
20	Profilometer Apparatus Used by Semi-Conductor Division of Westinghouse Electric	63
21	Schematic of Profilometer Apparatus	63
22	Typical Pre-Test Surface Profilometer Traces	64

LIST OF FIGURES (Continued)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
23	Typical Post-Test Profilometer Tracings	65
24	WESTF Test 50 Hardware	67
25	Typical Electrode Surfaces, WESTF Test 50	69
26	Exploded View, WESTF Test 50	71
27	Exploded View, WESTF Test 50	72
28	WESTF Cooling Water Subsystem Schematic	75
29	Individual Electrode Pair Circuit for Operation of WESTF with Magnet	78

I. ABSTRACT

Technical progress under DOE Contract DE-AC-01-79-ET-15529 during the October to December 1980 quarter is presented.

Emphasis within this program is directed towards the engineering development of cold metallic electrodes which are alternatives to the continued use of platinum as an anode clad material. Results of continuing laboratory screening tests, which have currently concentrated on materials previously tested by AVCO and other available commercial alloys, are presented. Improvements in the anode arc test methodology and test setup, which have resulted in improved reproducibility as well as test simplification, are discussed. Laboratory electrochemical corrosion testing has been initiated using aqueous and molten salts as the aggressive constituent in the electrolyte. Initial results from these tests are reported. On the basis of these test results, electrochemical corrosion tests using a molten salt are preferred.

As a result of ongoing laboratory screening tests, acceptance criteria, which are interim in nature and are likely to change based on future test results have been defined for the anode arc and electrochemical corrosion tests. Reflecting the initial laboratory test results, a listing of candidate advanced alloys which should demonstrate improved corrosion resistance has been defined. Fabrication of these alloys is anticipated during the next quarter.

Upon completion of WESTF modifications, facility checkout and activation operations have been initiated. Progress, as well as those difficulties which have been encountered, in completing WESTF activation is reported.

Detailed engineering and test planning activities in support of WESTF tests are reported.

II. OBJECTIVE AND SCOPE OF WORK

The overall objective of this program is to develop economic MHD electrode and insulator designs that will sustain long term open-cycle, coal-fired MHD generator operations. This program provides the link between basic and supportive materials development and testing in an engineering test rig that offers an actual MHD generator environment for extended periods of time.

Major research and development activities of this program are as follows:

- (a) Engineering rig tests of candidate electrode designs, selected on the basis of the screening test results and/or pertinent outside data, under simulated open-cycle coal-fired MHD operating conditions.
- (b) Laboratory screening tests to provide preliminary electrochemical stability data and to evaluate the resistance to simulated arc impingements on selected, advanced metallic and non-metallic candidate electrode materials and insulator materials.
- (c) Preparation and fabrication of experimental electrode materials, as warranted by favorable laboratory screening test results, to provide samples for engineering rig tests.
- (d) Verification and correlation of engineering rig test results with other DOE contractor test findings.

The products of this program will contribute directly to the near term goals of the MHD Component Development and Integration Facility (CDIF) Program and the longer range goals of the ETF Program.

The program schedule has the following primary milestones:

● Define Screening Test Criteria - Anode Arc	- 10/80
● Define Screening Test Criteria - Electrochemical	- 11/80
● Complete Cu Correlation Verification	- 4/81
● Complete Pt Correlation Verification	- 5/81
● Define WESTF Test Criteria	- 6/81

- Achieve 375 Hours Cumulative Test Time (WESTF) - 3/82
- Complete Final Cold Metallic Test - 3/83
- Complete Fabrication Development (Cold Wall) - 3/83
- Complete Material Archive - 3/83
- Recommend Alternative Electrodes - 3/83

The major elements of the program are presented in a Work Breakdown Structure (WBS) which is given in Table 1. The Level I effort is the MHD Generator Electrode Development Program Contract, with Level II consisting of the five major tasks as follows:

- WBS 1.1 ELECTRODE/INSULATOR MATERIALS
- WBS 1.2 ENGINEERING TESTS
- WBS 1.3 WESTF OPERATIONS
- WBS 1.4 WESTF GENERATOR CORRELATION
- WBS 1.5 PROJECT MANAGEMENT

WBS 1.1 - ELECTRODE/INSULATOR MATERIALS

The objective of this task is to select potential candidate MHD electrode/insulator materials through a process of investigative analysis, development, laboratory evaluation and fabrication of these materials for more extensive engineering rig tests simulating MHD generator environments. All necessary experimental material preparation, as well as fabrication of test samples for laboratory screening tests, engineering rig tests, or other tests will be completed under this task. This task also includes supporting pretest material characterization and laboratory screening tests used to evaluate the relative performance of candidate materials. These screening tests include electrochemical and electrode arc impingement tests.

WBS 1.2 - ENGINEERING TESTS

The objective of this task is to select candidate electrode/insulator materials from the engineering test results of promising electrode/insulator materials based on WBS 1.1 activity. These candidate materials will then be recommended for use and testing in an actual MHD generator. In particular, this task

TABLE 1: WORK BREAKDOWN STRUCTURE

WBS 1.0 - MHD GENERATOR ELECTRODE DEVELOPMENT

WBS 1.1 - ELECTRODE/INSULATOR MATERIALS

WBS 1.1.1 - Materials Research

- Investigative Research
- Development Requirements/Criteria
- Material Characterization

WBS 1.1.2 - Laboratory Screening Tests

- Electrochemical Corrosion
- Arc Impingement

WBS 1.1.3 - Fabrication Development

- Process Development
- Experimental Material Fabrication

WBS 1.2 - ENGINEERING TESTS

WBS 1.2.1 - Test Engineering

- Test Planning/Experiment Design
- Post-Test Analysis/Characterization
- Material Archive

WBS 1.2.2 - Fabrication

- Test Section
- Test Electrode/Insulators

WBS 1.3 - WESTF OPERATIONS

- Maintenance and Modifications
- Checkout Operations
- Test Operations

WBS 1.4 - WESTF GENERATOR CORRELATION

- Verification Plan
- Develop Correlations

WBS 1.5 - PROJECT MANAGEMENT

- Coordination
- Documentation

I

II

III - SYSTEMS LEVEL

provides for the supporting design, test and post-test analysis effort as well as maintenance and operation of the engineering test rig. This task incorporates the elements of planning, experiment design, and post-test analysis and provides the close engineering design and test discipline necessary to effect successful electrode/insulating wall system development. Also included under this task is the final fabrication and assembly operations necessary to incorporate electrode and interelectrode insulating elements into a complete assembly ready for testing.

Detail electrode design parameters - i.e., materials, thermal conditions and configuration will be established reflecting test and generator performance results through two sources: first, analysis and merit ranking of screening test results and, second, pertinent experimental data as it becomes available through external related work such as the AVCO Mark VI and VII test experience.

WBS 1.3 - WESTF OPERATIONS

The objective of this task is to complete dynamic rig testing of selected electrode and insulator designs in a small scale MHD generator. The Westinghouse Electrode System Test Facility (WESTF) has the following nominal characteristics:

Mass Flow	To 0.5 lb/sec
Combustion Temperature	To 2850 K
Combustor Pressure	1 to 5 atm
Channel Velocity	Subsonic, 500 to 800 m/sec
Seeding	K_2CO_3 or K_2SO_4 wet with ash or char additions (Rosebud)
Magnetic Field	3 Tesla, nominal 3.3 Tesla, objective
Fuel	#2 Diesel Fuel Oil
Oxidant	Preheated air with oxygen enrichment
Data Collection	240 channels coupled with minicomputer
Test Duration Capability	Up to 100 hours
Test Frequency	Up to 2 per month
Channel Configuration	12.5 cm flow cross section
Maximum Active Length	38 cm
Startup Ramp, Minimum	25 K/min

This task also supports modifications to the WESTF engineering test rig as required to accommodate the test program.

WBS 1.4 - WESTF GENERATOR CORRELATION

The objective of this task is to correlate and verify the test results on electrode materials that have been obtained with the WESTF engineering test rig with the results of other DOE contractors performing research on MHD electrodes. This direct comparison analysis effort shall address two distinct phases of WESTF operations; testing performed without an electromagnetic field, and the testing conducted with an electromagnetic field. Specific work elements under this task are:

- Develop a verification plan and approach that will provide the basis for the analytical and physical evaluation of WESTF and other DOE contractor test results.
- Perform analytical analyses and develop correlations (if possible) on selected electrode material test results that are currently available.
- Compare WESTF testing with magnet to other contractors' testing with magnetic fields.

WBS 1.5 - PROJECT MANAGEMENT

This centralized management task provides the focal point for directing the activities which comprise the full project effort. The Project Manager shall provide the proper definition, integration and implementation of the technical, schedule, contractual, and financial aspects of the program. Coordination of the preparation of required project documentation will also be completed under this task.

III. SUMMARY OF PROGRESS TO DATE

During the October to December 1980 quarter, the principal areas of activity were as follows:

- Definition of improved procedures applicable to the anode arc test of anode clad materials.
- Continuation of the evaluation of available commercial alloys via anode arc tests.
- Initiation of the evaluation of available commercial alloys by means of electrochemical corrosion tests, including the comparative evaluation of specific electrochemical tests.
- Definition of specific acceptance criteria applicable to the anode arc and electrochemical corrosion laboratory screening tests.
- Detailed engineering activities in support of WESTF Tests 50, 51, 52, 53 and 54.
- Fabrication and assembly activities in support of WESTF Tests 50, 51, 52 and 54.
- Continuation of WESTF checkout and activation activities.
- Revision of required WESTF operating procedures to reflect facility modifications associated with the magnet addition.

Figure 1 summarizes the overall program schedule, based on the approved Project Management Summary Baseline Report, FY 81 revision dated October 1980, and shows schedular status. A revised WBS was instituted effective FY 81 to reflect emphasis to be directed to the engineering development of slagging cold metallic electrodes. The following summaries of progress reflect the current areas of emphasis; summaries of the prior activities which were directed towards refractory electrodes are contained in Reference 1.

U.S. DEPARTMENT OF ENERGY
MILESTONE SCHEDULE AND STATUS REPORT

1. Contract Identification		MHD GENERATOR ELECTRODE DEVELOPMENT PROGRAM		2. Reporting Period		through 12/80		3. Contract Number		DE-AC-01-79-ET-15529																	
4. Contractor (name, address)		WESTINGHOUSE ELECTRIC CORPORATION Advanced Energy Systems Division P. O. Box 10864 Pittsburgh, PA 15236		5. Contract Start Date		April 23, 1979		6. Contract Completion Date		March 31, 1983																	
7. Identification Number	8. Reporting Category (e.g., contract line item or work breakdown structure element)	9. Fiscal Years and Months												10. Percent Complete													
WBS		81 82 83																									
		O	N	D	J	F	M	A	M	J	J	A	S	1Q	2Q	3Q	4Q	1Q	2Q					a) Planned	b) Actual		
1.1	ELECTRODE AND INSULATOR MATERIALS																										
1.1.1	MATERIALS RESEARCH																										
1.1.2	LABORATORY SCREENING TESTS																										
1.1.3	FABRICATION DEVELOPMENT																										
1.2	ENGINEERING TESTS																										
1.2.1	TEST ENGINEERING																										
1.2.2	FABRICATION																										
1.3	WESTF OPERATIONS																										
1.4	WESTF GENERATOR CORRELATION																										
1.5	PROJECT MANAGEMENT																										
11. Remarks																											
12. Signature of Contractor's Project Manager and Date													13. Signature of Government Technical Representative and Date														
John W. Sadler																											

Figure 1. Program Schedule and Status

1.0 WBS 1.1 ELECTRODE AND INSULATOR MATERIALS

Selection of potential candidate electrode/insulator materials through a process of investigative analysis, laboratory evaluation and development is accomplished within this task. In addition, this task provides for fabrication development of advanced materials as well as supporting pretest material characterization.

In keeping with the emphasis being given to the development of alternatives to platinum as an anode clad material, a literature search concentrating on hot corrosion and arc erosion has been completed. Primary conclusions from this study, discussed in detail in Reference 1, are as follows:

- The prime candidate anode materials are chromium based alloys containing small additions of rare earth elements and yttrium and/or stable oxide dispersoids.
- The next most promising candidate materials in order of preference are Co and Fe based binary or ternary alloys containing a minimum of 25-30 w/o Cr.
 - Ni based alloys have been shown to demonstrate low corrosion resistance based on laboratory tests reported in Section IV-1.2. Further there are indications from laboratory screening test results, which are incomplete at this point in time, which could result in a reordering of the order of preference for chromium-based, cobalt-based and iron-based alloys. This indication is not unexpected since the above order of preference is based on hot corrosion only while the laboratory screening tests are more representative of the MHD generator environment.
 - Additives such as W, Mo, Nb and Ta, which are employed to improve high temperature strength contribute to a lack of corrosion resistance.
- Additions of more than 8 w/o Al and platinum additions at the 5-10 w/o level are promising.
- Coating alloys or copper with corrosion resistant materials such as CoCrAlY and FeCrAlY, as well as with ceramics such as TiB_2 , may minimize arc attack.

Laboratory electrochemical corrosion tests and anode arc erosion tests have been conducted to evaluate the relative performance of candidate electrode materials. The following summarizes significant findings in these areas:

- A comprehensive model for understanding electrochemical reactions in slagging MHD channels has been developed (Reference 2).
- Slag chemistry modification, through additions of transition metal ions, is effective in minimizing electrochemical corrosion and polarization (Reference 3).
- Laboratory scale anode arc tests indicate that TiB_2 coated copper may be comparable to platinum clad copper in the slagging cold operating mode (Reference 4).

Continuing results from the laboratory anode arc tests are presented in Section IV-1.2. Further improvements in test methodology have been established and, as a result, retesting of materials has been initiated using the new test setup. Table 2 provides a status summary of the anode arc laboratory screening tests.

Laboratory electrochemical corrosion testing was initiated this quarter and initial results are presented in Section IV-1.2. The status of these tests is also indicated in Table 2. Electrochemical corrosion tests have been completed with aqueous solutions and molten salts as the electrolyte. As discussed in Section IV-1.2, no further testing with aqueous solutions is anticipated.

Based on results obtained to date, acceptance criteria for materials have been defined for the laboratory screening tests and are as follows:

- Anode Arc Test
 - at 375°C $\leq 6 \mu\text{g/C}$
 - at 500°C $\leq 12 \mu\text{g/C}$
- Electrochemical Corrosion Test
 - molten KHSO_4 $\leq 10 \mu\text{g/C}$

TABLE 2. LABORATORY SCREENING TEST SUMMARY

MATERIALS	ELECTROCHEMICAL CORROSION TESTS					ANODE ARC TEST		MATERIALS
	Aqueous K ₂ SO ₄ 80°C	Aqueous KHSO ₄ 80°C	Molten KHSO ₄ 300°C	Molten K ₂ S ₂ O ₇ 500°C	Molten K ₂ SO ₄ 1100°C	Sample 0 375°C	Sample 0 500°C	
<u>AVCO ALLOYS</u>								<u>AVCO ALLOYS</u>
330SS	0	0	0	0	0	0	0	330SS
IN601	0		0	0	0	0	0	IN601
20Cb3	0		0	0	0	0	0	20Cb3
446SS	0		0	0	0	0	0	446SS
EB26-1	0		0	0	0	0	0	EB26-1
Pt			0	0	0	0	0	Pt
<u>COMMERCIAL</u>								<u>COMMERCIAL</u>
EB26-16	0		0			0	0	EB26-16
EB29-4	0		0	0	0	0	0	EB29-4
FeCrAlY	0		0	0	0	0	0	FeCrAlY
309SS			0			0	0	309SS
310SS	0		0	0	0	0	0	310SS
406SS	0	0	0	0	0	0	0	406SS
IN 671	0	0	0	0	0	0	0	IN 671
IN 690	0	0	0	0	0	0	0	IN 690
304SS	0	0	0	0	0	0	0	304SS
RA333			0					RA333
Haynes 188	0	0	0	0	0	0	0	Haynes 188
Haynes 150			0			0	0	Haynes 150
Haynes 6B			0	0	0	0	0	Haynes 6B
Incoloy 800			0	0	0	0	0	Incoloy 800
Tool Steel (6% Cr)			0	0		0	0	Tool Steel (6% Cr)
Fe			0					Fe
Ni			0					Ni
Co	0		0	0	0		0	Co
Ti	0		0	0	0		0	Ti
Cr			0					Cr
<u>ADVANCED</u>								<u>ADVANCED</u>
Cr-Y (1%)	0	0	0	0	0	0	0	Cr-Y (1%)
CoCrAlY			0	0	0	0	0	CoCrAlY
82Fe18Cr			0	0	0	0	0	82Fe18Cr
70Fe30Cr			0	0	0	0	0	70Fe30Cr
65Fe30Cr5Al(Y)			0	0	0	0	0	65Fe30Cr5Al(Y)
50Fe50Cr			0	0	0	0	0	50Fe50Cr
77Fe18Cr5Pt			0	0	0	0	0	77Fe18Cr5Pt
72Fe18Cr10Pt			0	0	0	0	0	72Fe18Cr10Pt
60Co10Fe30Cr			0	0	0	0	0	60Co10Fe30Cr
55Co10Fe30Cr5Al(Y)			0	0	0	0	0	55Co10Fe30Cr5Al(Y)
67Co10Fe18Cr5Pt			0	0	0	0	0	67Co10Fe18Cr5Pt
EB26-1 + 5Pt			0	0	0	0	0	EB26-1 + 5Pt
EB26-1 + 10Pt			0	0	0	0	0	EB26-1 + 10Pt
Haynes 150 + 5Pt			0	0	0	0	0	Haynes 150 + 5Pt
Haynes 150 + 10Pt			0	0	0	0	0	Haynes 150 + 10Pt
406SS + 5Pt			0	0	0	0	0	406SS + 5Pt
406SS + 10Pt			0	0	0	0	0	406SS + 10Pt
<u>NON-METALS</u>								<u>NON-METALS</u>
TiB ₂			0	0	0	0	0	TiB ₂
SiC			0	0	0	0	0	SiC
Mo ₂ S ₃			0	0	0	0	0	Mo ₂ S ₃
AlPt ₃			0	0	0	0	0	AlPt ₃
Y ₂ CrO ₃			0	0	0	0	0	Y ₂ CrO ₃
Cr ₂ O ₃			0	0	0	0	0	Cr ₂ O ₃
SnO ₂			0	0	0	0	0	SnO ₂

0 - PLANNED 0 - COMPLETED

With regard to laboratory screening tests there is a general correlation with results obtained by AVCO in their generator tests. Further testing is, however, required.

A number of advanced alloys have been defined based on the results of our literature survey and subsequent laboratory screening test results. These alloys are identified in Table 2 and fabrication will be initiated next quarter.

2.0 WBS 1.2 - ENGINEERING TESTS

The objective of this task is to provide the engineering support required for the conduct of WESTF tests under WBS 1.3 of promising electrode/insulator materials resulting from the WBS 1.1 activity. In particular, this task provides for the detail test planning, test section design and post-test analysis effort. In comparison with laboratory screening tests which generally couple only one or two aspects of the MHD channel environment, WESTF testing provides a realistic simulation of the MHD channel environment.

In consonance with the emphasis to be placed on the engineering development of slagging cold metallic electrodes and at the same time to provide support for the investigation of the performance of hot electrode materials, to be supplied by others, an overall WESTF Test Plan has been defined (Reference 1).

A WESTF-Generator Correlation Plan has been defined wherein the initial WESTF tests emphasize obtaining the data to be used in verifying the correlation between WESTF and AVCO Generator test results (Reference 1).

Two generic test section configurations have been defined for use in evaluating materials and electrode designs as part of this program effort. These test sections are as follows:

- WESTF Test Section, which includes the capability of investigating magnetic field effects (Reference 1).
- Materials Test Section (MTS), to be used for screening electrode materials, excluding magnetic field effects (References 1 and 3).

During this quarter, analyses have been completed in support of the basic test section design (MTS) and in support of the detail design of the specimens included in planned WESTF and MTS tests (see Section IV-2.1).

Table 3 provides a summary of planned WESTF Tests, WESTF Test 50 through WESTF Test 54, and reflects changes implemented during this quarter. Status of the fabrication and assembly activity is presented in Section IV-2.2.

3.0 WBS 1.3 - WESTF OPERATIONS

Activity within this task is directed towards the conduct of WESTF testing and includes those modifications which are necessary to extend WESTF capabilities and incorporate facility and operational improvements. The primary modification to be completed is the addition of a conventional 3 Tesla magnet to WESTF such that magnetic field effects can be reflected in the engineering testing of electrode and insulator materials and designs.

At the completion of WESTF Test 49 in mid-March 1980, the facility was shut down for those modifications required by the magnet addition.

Extensive modification and rework of the facility has been completed as follows:

- Magnet modification (Reference 5)
- WESTF subsystem rework and modification (Reference 1).

Facility activation, including subsystem checkout, is in progress and is discussed in Section IV-3.0. Discussions are also presented relative to the procurement of a new data logger, to replace the KAYE Instruments, and the modification of the existing scrubber system to permit operation at high sulfur levels in the gas stream.

4.0 WBS 1.4 - WESTF-GENERATOR CORRELATION

The objective of this task is to correlate and verify the test results on electrode materials obtained in WESTF with the results obtained in the AVCO Generator tests.

TABLE 3. SUMMARY OF PLANNED WESTF TESTS

REVISION AS OF 12/30/80

TEST ID	50	51	52	53	54	
Operating Mode	Cold	Cold	Super-Hot	Cold	Super-Hot	
Test Section	WESTF	MTS	MTS	WESTF	MTS	
Electrode Material ⁽¹⁾ (2)	(+) Cu (16) (-) W-Cu (8) (-) Cu (8)	(+) IN 671 (1) (+) EB 26-1 (1) (+) TiB ₂ (1) (+) 304 ² SS (1)* (-) W-Cu (4) * RUN 2 (+) 310 SS (1)* (+) EB 29-4 (1)* (+) FeCrAlY (1)* (+) Haynes 150**	(+) A-LLL (2) ⁽³⁾ (+) A-MMM (2) (-) A-LLL (2) (-) B-MMM (2)	(+) Cu (2) (+) Pt (4) ⁽⁴⁾ (+) HAYNES 150(2) (+) IN 671 (2) (+) EB 26-1 (2) (+) EB 29-4 (2) (+) 310SS (2) (-) W-Cu (16)	(+) A-LLL (4) ⁽³⁾ (-) B-MMM (1) (-) A-LLL (3)	
Insulator Material	BN	BN	MgO	BN	MgO	
T _E , °C	125 & 275	~ 150	1600*	~225*	TBD*	
J, amp/cm ²	1.0	1.0	0.75 & 1.0	1.0	1.0	
Q, w/cm ²	~125	~125	~60	~125	~60	
B, Tesla	0 & 3	0	0	3	0	
Ash/Seed Type	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	
Sulfur, w/o	0.05	0.14	0.14*	0.14*	0.14*	
Duration-Hrs.	~20	~20	10-20	~20	10-20	

(1) ANODE AND CATHODE UNLESS OTHERWISE NOTED.

(2) BRACKETS DEFINE NUMBER OF ELECTRODES

(3) HAFNIA BASED MATERIALS SUPPLIED BY RPML.

(4) AVCO REFERENCE ELECTRODES.

(5) *DENOTES CHANGE INCORPORATED IN THIS ISSUE.

In this regard, a WESTF-Generator Correlation Plan was defined as part of the overall planning activity completed as part of WBS 1.2. Analysis of WESTF data, and subsequent verification of a correlation will commence when WESTF test results are available for WESTF Tests 50, 53, 55 and 56.

5.0 WBS 1.5 - PROJECT MANAGEMENT

The objective of this task is to provide a focal point for directing and coordinating the activities which comprise the full project effort. Coordination of the preparation of required project documentation is also accomplished within this task.

Significant project documentation issued during this quarter included the following:

- Quarterly Report, July-September 1980.
- Monthly Project Management Reports
- Project Management Summary Baseline Report, October 1980, Final Issue.

IV. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

1.0 WBS 1.1 - ELECTRODE AND INSULATOR MATERIALS

1.1 WBS 1.1.1 - Materials Research

The wastage, or loss of material, of anodes in a slagging cold wall MHD generator is due to some combination of two interacting degradation mechanisms, namely, hot corrosion and arc erosion. This is illustrated in Figure 2 which shows an arc impinging on a slag coated metal anode and its protective oxide scale.

Near the center of the arc column, the slag, the alloy scale and to a lesser extent, the alloy itself, is vaporized while in the cooler regions radially outward from the column, designated by (L), melting reactions occur. Because of a voltage gradient between the plasma and the anode, anions such as O^{-2} and SO_4^{-2} , in both the vapor and liquid phases, are electrochemically driven towards the anode where they are discharged according to the reactions.

and

At elevated temperatures, the presence of these oxidizing-sulfurous atmospheres gives rise to accelerated chemical degradation of alloys known as hot corrosion. Anode arc erosion loss is comprised of the vaporization/melting of oxide scales and/or alloys, as well as the physical spalling of the protective scales due to mechanical and thermal stresses generated by the impinging arc. Although there is little experimental work detailing arc attack mechanisms, it is clear that anode alloy selection criteria should be based on its being refractory and on its having a refractory protective scale. In addition, the scale must have: high thermal and electrical conductivity; high thermal shock resistance, and high resistance to being fluxed by molten slag/seed mixtures.

The scenario described above illustrates that the degradation of anode materials in MHD generators is very complex and, at the same time, not well defined. To

Figure 2. Schematic of Arc Impingement on Slag Covered Alloy Anode

simulate the degradation of anodes in a relatively simple laboratory test is, therefore, not a simple task. However, the incentive is attractive; laboratory tests are inexpensive, they have very short turnaround times and they require small amounts of test material. A screening test or tests that truly simulates the degradation effects occurring in large MHD generators can serve as a powerful tool in accelerating electrode development. Given that degradation is due to some combination of arc erosion and electrochemical corrosion, Westinghouse has taken the approach of developing, first, a laboratory test that provides a strong arc erosion component and secondly, a laboratory test that provides the electrochemical corrosion component.

Anode arc experiments have been conducted for some time. In this quarter, further refinements to this test have been made to improve the reproducibility of test results. Acceptance and rejection criteria were established for this test based on results obtained to date; materials with losses greater than $6 \mu\text{g/C}$ at 375°C and $12 \mu\text{g/C}$ at 500°C are to be rejected. Materials which demonstrate lower losses will be accepted for further evaluation. However, the recent modifications to this test may require an adjustment in these criteria. It is also expected that as additional test results are available, further revisions to these criteria may be justified.

Electrochemical corrosion testing of cold wall anode materials was initiated this quarter. Since the temperatures created on electrode surfaces and the composition of the melt around the arc are ill defined, it is necessary to evaluate metals in several electrolytes over a wide range of temperatures. Table 4 includes the categories of AVCO tested materials and commercial alloys, and summarizes the current status of screening tests. The solid circles represent completed tests while the open circles represent tests planned. The planned tests (open circles) shown in Table 4 should be completed in the next quarter. Table 4 also indicates the near-term WESTF tests where selected alloys will be tested and evaluated as an electrode in the MHD generator environment. For these alloys, comparisons between the WESTF test results and the screening test results will provide the understanding and the confidence necessary to establish a test or combination of tests for the further evaluation of materials.

TABLE 4. COMMERCIAL ALLOY TEST SUMMARY

MATERIAL	LABORATORY ELECTROCHEMICAL TEST					LABORATORY ANODE ARC TEST		WESTF ELECTRODE TEST	
	Aqueous K_2SO_4 80°C	Aqueous $KHSO_4$ 80°C	Molten $KHSO_4$ 300°C	Molten $K_2SO_4 \cdot 0.7$ 500°C	Molten K_2SO_4 1100°C	Sample @ 375°C	Sample @ 500°C		
AVCO ALLOYS									
330SS	●	●	●	0	0	0	0		
IN601	●		●	0	0	0	0		
20Ch3	●		●	0	0	●	●		
446SS	●		●	0	0	●	●	051	053
EB26-1			●	0	0	0	0		053
Pt									
COMMERCIAL									
EB26-1	●		●			0	0		
EB29-4	●		●	0	0	0	0	051	
FeCrAlY	●		●	0	0	0	0	051	
309SS	●		●			0	0		053
310SS	●	●	●	0	0	0	0		
406SS	●	●	●	0	0	0	0	051	053
IN 671	●		●	0	0	0	0		
IN 690	●	●	●	0	0	●	●	051	
304SS			●						
RA333			●			0	0		
Haynes 188	●	●	●	0	0	0	0	051	053
Haynes 150			●			0	0		
Haynes 68	●		●	0		0	0		
Incoloy 800			●	0		●	●		
Tool Steel			●						
Fe			●						
Ni			●						
Co			●						
Ti	●		●	0	0		●		
Cr	●		●	0	0		0		

0 - PLANNED ● - COMPLETED

Additional screening tests will be conducted on two other classes of materials. The first class is identified as Advanced Alloys, i.e., non-commercial alloys whose compositions are derived from screening test results on commercial alloys. These alloy compositions are shown in Table 5. These alloys are based upon the cobalt-chromium and iron-chromium binary systems. The effect of chromium level on corrosion/erosion resistance will be evaluated. Additions of aluminum and yttrium to these base alloy compositions will demonstrate the effect of FeCrAlY type alloys. Additions of platinum at the 5-10 w/o level will be made to three promising commercial alloys (406 stainless, EB 26-1 and Haynes 150). Enhanced resistance to oxidation and corrosion in aggressive high temperature environments by the addition of small quantities of platinum to several superalloys has been reported (Reference 6). Chromium based alloys with Y_2O_3 , Y, or $YCrO_3$ additions will be considered on the basis of the formation of electrically conductive ($YCrO_3$) scales. Most of these alloys will be fabricated at Westinghouse using vacuum arc melting or vacuum levitation melting techniques.

The second class of materials to be considered are highly conducting non-metals. These materials are also shown in Table 5. These will be tested in monolithic or coating form, whichever is most convenient.

1.2 WBS 1.1.2 - Laboratory Screening Tests

1.2.1 Electrochemical Corrosion Tests

Generator test result reported by AVCO (Reference 7) and previously by Heywood and Womack (Reference 8) both strongly indicate that electrochemical reactions with sulfate deposits are a major, if not the primary contribution to anode material loss. Since the local temperatures on anode surface under the arcs could range from $100^{\circ}C$ to well over $1000^{\circ}C$ the composition of the potassium sulfate compounds could vary. Below $100^{\circ}C$ the condensation of water vapor from the gas stream in combination with potassium sulfate deposits would create aqueous potassium sulfate (K_2SO_4) or potassium bisulfate electrolyte solutions. The British found a very good correlation between electrochemical corrosion test results using aqueous K_2SO_4 solutions flame erosion test rig and/or generator test erosion losses (References 8 and 9). In the temperature range from 100 to $205^{\circ}C$ a mixture of solid K_2SO_4 and $KHSO_4$ can form. At $205^{\circ}C$

TABLE 5. ADVANCED METALS AND NON-METALS COMPOSITIONS

MATERIAL	LABORATORY ELECTROCHEMICAL TEST					LABORATORY ANODE APC TEST		WESTF ELECTRODE TEST
	Aqueous K ₂ SO ₄ 80°C	Aqueous KHSO ₄ 80°C	Molten KHSO ₄ 300°C	Molten K ₂ SO ₇ O ₇ 500°C	Molten K ₂ SO ₄ 1100°C	Sample @ 375°C	Sample @ 500°C	
<u>ADVANCED ALLOYS</u>								
82Fe18Cr			0	0	0	0	0	
70Fe30Cr			0	0	0	0	0	
65Fe30Cr5Al0.1Y			0	0	0	0	0	
50Fe50Cr			0	0	0	0	0	
77Fe18Cr5Pt			0	0	0	0	0	
72Fe18Cr10Pt			0	0	0	0	0	
CoCrAlY (Cr~15, Al~12)			0	0	0	0	0	
60Co10Fe30Cr			0	0	0	0	0	
55Co10Fe30Cr5Al0.1Y			0	0	0	0	0	
67Co10Fe18Cr5Pt			0	0	0	0	0	
EB26-1 + 5% Pt			0	0	0	0	0	
EB26-1 + 10% Pt			0	0	0	0	0	
406SS + 5% Pt			0	0	0	0	0	
406SS + 10% Pt			0	0	0	0	0	
Haynes 150 + 5% Pt			0	0	0	0	0	
Haynes 150 + 10% Pt			0	0	0	0	0	
<u>NON-METALS</u>								
TiB ₂			0	0	0	0	0	
SiC			0	0	0	0	0	
Mo ₂ Si			0	0	0	0	0	
AlPt ₃			0	0	0	0	0	
Y ₂ CrO ₃			0	0	0	0	0	
Cr ₂ O ₃			0	0	0	0	0	
SnO ₂			0	0	0	0	0	

0 - PLANNED 0 - COMPLETED

potassium bisulfate melts with an expected increase in reactivity with metal alloys. With increasing temperatures KHSO_4 decomposes to form potassium pyrosulfate;

Around 360°C , depending somewhat on the partial pressure of water vapor, conversion of KHSO_4 to $\text{K}_2\text{S}_2\text{O}_7$ is complete. Above 400°C , SO_3 is driven from the pyrosulfate with K_2SO_4 as the reaction product;

Again depending upon the SO_3 partial pressure this reaction is complete at about 750°C . In the range of 750 to 1050°C solid K_2SO_4 is the deposit, while liquid K_2SO_4 is present above these temperatures. This scenario is illustrated in Figure 3 which shows the weight loss for KHSO_4 as a function of temperature in a nitrogen atmosphere. There is an initial weight loss occurring between 200 and 300°C where H_2O is driven off and a second weight loss between 450 and 600°C where SO_3 is driven off. In the MHD generator, where the partial pressures of H_2O and SO_3 are much higher, these weight losses will occur at somewhat higher temperatures.

Given the possibility of several sulfate-based electrolytes as deposits in the MHD generator, a series of electrochemical corrosion tests will be conducted including the following:

- aqueous K_2SO_4 at 80°C
- molten KHSO_4 at 300°C ,
- molten $\text{K}_2\text{S}_2\text{O}_7$ at 500°C and;
- finally, molten K_2SO_4 at 1100°C .

Comparison of test results between these tests and tests on the same metals in WESTF will permit the selection of a preferred electrochemical test for future materials screening. Since the conditions in these tests are far better defined than those in WESTF, actual corrosion mechanisms in WESTF could be identified by comparative post-test materials analysis.

Figure 3. Weight Loss of KHSO_4 versus Temperature in Nitrogen Atmosphere

For all of the electrochemical tests the test arrangement shown in Figure 4 is very similar. The anode test specimen is partially (1.0 cm^2 area) immersed into the electrolyte along with a platinum cathode. A platinum reference electrode is also inserted to measure anode-cathode, anode-reference and cathode-reference voltages. These voltages are monitored using a digital multimeter and a six channel strip chart recorder. Temperatures are measured with a thermocouple inserted into the electrolyte. Although not shown in Figure 4, the pH of aqueous solutions was measured with a pH meter. In the molten K_2SO_4 and K_2SO_4 experiments an additional sample of the anode alloy was inserted. The purpose of this sample is to compare reactions and weight changes between similar anode samples with and without current flow.

By the end of 1980 two series of electrochemical experiments had been completed on the AVCO and other commercial alloy, the aqueous K_2SO_4 and the molten KHSO_4 . In addition, a few pure metals were tested in an aqueous KHSO_4 solution. These aqueous KHSO_4 experiments were added, largely, because the anode arc tests use molten KHSO_4 as the corrodent. Emphasis to date has been on completing as many tests as possible and little effort has been directed to the post-test materials characterization. Until this characterization work is complete the experimental data will be reported with a minimum of interpretation. In order to confirm the validity of the laboratory screening tests, it is necessary to evaluate these results against those which will be obtained in WESTF and generator tests.

In Table 6 the results of electrochemical tests to date are reported along with available Mark VII erosion data reported by AVCO (References 1 and 10). The materials in Table 6 are commercial alloys plus a few pure metals. The commercial alloys are chromium containing alloys based upon some combination of iron, cobalt, or nickel. Although the list of metals tested in this program is more extensive, the results are in excellent agreement with those of the earlier British studies. Based upon this agreement in results, Womack's (Reference 8) results on nickel, iron, cobalt, titanium, platinum and copper are also included in Table 6. The results in aqueous K_2SO_4 solution can be rationalized if we considered a phenomenological description of electrolytic electrode erosion. Erosion will occur when metal ions become detached from the metal lattice and either go into solution or form a compound that spalls off the electrode at the current density used.

Figure 4. Schematic of Electrochemical Corrosion Test

TABLE 6. ELECTROCHEMICAL CORROSION RATES OF METAL ALLOYS IN POTASSIUM SULFATE ELECTROLYTES

ALLOY	COMPOSITION							Aqueous K ₂ SO ₄	Aqueous KHSO ₄	Molten KHSO ₄	AVCO* MARK VII
	Fe	Ni	Cr	AL	Mo	Co	Other				
Iron	100							(67)	---	1.6	---
Tool Steel	92		5		1		1C 4.5 Mn	---	---	1.7	---
406SS	83		13	4			0.1 Y	18	84	4.7	---
FeCrAlY	80		15	5			0.1 Ce	33	---	5.5	---
446SS	72.5		25				1.0 Si 1.5 Mn	---	---	5.6	---
E 26-1	73		26		1			41	---	5.6	3.5
E 26-1S	72		26		1		1 Si	32	---	5.2	---
E 29-4	67		29		4			53	---	7.5	---
304SS	70	9	19		1.5			25	99	8.7	---
309SS	60	14	23		0.3		1.8 Mn, 0.7 Si	---	---	36.0	---
310SS	52.5	21	25				1.5 Si	163	---	42.0	---
Incoloy 800	44	32.5	21		0.4		0.8 Mn, 0.4 Ti 0.55 Si	178	---	60.0	---
20 Cb-3	40	33	20		2		0.3 Si, 3.3 Cu 0.5 Mn, 0.5 Cb	182	---	54.0	4.6
330SS	43	35	19.5				1 Si, 1.8 Mn	178	181	65.0	7.8
IN 601	14	60.5	23	1.35				182	---	105.0	8.9
IN 690		70	30					182	---	92.0	---
IN 671		52	48					253	153	128.0	---
Nickel		100	100					(22)	---	102.0	---
Platinum							100 Pt	(1)	---	0.8	0.5-0.6
Cobalt						100		(239)	---	22.0	---
Haynes 150	21		28			50		200	182	5.0	---
Haynes 188	3	22		14.5 W		36		---	---	145.0	---
Haynes 68	1.9		28	4.5 W 4.5 W		57		---	---	157.0	---
Chromium			100					98	---	132.0	---
Titanium							100 Ti	(8)	---	134.0	---
Copper							100 Cu	(340)		653.0	150

() From Reference 8.

*700K (Reference 10).

For example, these reactions can be stated simply as

and

If these reactions are dominant, erosion rates (E) will obey Faraday's Laws:

$$E (\mu\text{g C}^{-1}) = A/nF$$

where A = atomic weight of the element, n = the valency state and F = the Faraday constant ($0.0965 \text{C } \mu\text{g}^{-1} \text{ at wgt}^{-1}$). If we plot predicted Faradaic losses against our experimental data (Figure 5) it is obvious that copper, cobalt and chromium erosion obeys Faraday's Law while iron, nickel, titanium and platinum exhibit losses less than that predicted by Faraday's Law. The former, thus, form reaction products that go into solution or spall off and are non-protective.

Platinum, nickel and iron exhibited losses lower than that predicted by Faraday's Laws because they react to form a passivated layer, i.e., a low resistance oxide or hydroxide which is electronically conducting so that the electrolytic reaction occurs at the electrolyte/oxide or hydroxide layer interface. Passivation is dependent upon the pH of the solution. For example, copper is partly passivated in alkaline solutions (Reference 9).

On the other hand, titanium, forms an oxide layer that is insoluble, adherent, of high resistance, ionically conducting, of high free energy of formation and usually porous. This metal is called a 'valve' metal because of the rectifying properties of its oxide. The voltage to maintain a required current density rises to high values corresponding to oxygen evolution overvoltages for the oxide surface.

If we now consider the commercial alloys tested to date in this program they can be broken into those that exhibit Faradaic losses and those that are passivated. The former consists of the iron-chromium based alloys and 304 stainless steel, while the latter consists of the nickel containing (>9%) and cobalt based alloys.

Figure 5. Comparison of Electrolytic Anode Corrosion in Aqueous K_2SO_4 with Faradaic Loss

These results suggest an iron oxide, or perhaps Al_2O_3 in the case of 406 stainless and FeCrAlY, provides passivation. These solutions were slightly alkaline ($\text{pH} = 7-8.5$) and, with the exception of titanium, the total anode-cathode voltage drops for all samples were in the 5-8 volt range. In comparison, the results in the KHSO_4 solution show that the iron based alloys lose much of their passivation, most probably due to a change to a very acidic ($\text{pH} = 1.5$) solution. The other three alloys (330 stainless, Inconel 671 and Haynes 150) tested in KHSO_4 solutions reproduced their Faradaic losses.

The corrosion of metals and alloys in molten KHSO_4 appears to be quite different from that in aqueous K_2SO_4 solutions. First, most of the metals tested had losses less than the predicted Faradaic losses. Secondly, the degree of passivation or immunity demonstrated by the most resistant alloys is far better than that exhibited in aqueous solutions. The anode voltage drops, with a few exceptions, are in the 10-30 volt range which indicates the formation of protective electrically resistive layers or scales. In fact, within the Fe-Ni-Cr based alloys, the higher the anode voltage drop the lower the corrosion rate. This is illustrated in Figure 6 for five different stainless steels. The increase in voltage drop with time for 309 and 310 stainless steel can be interpreted as due to the growth of an oxide layer. Thirdly, there is a more uniform variation in corrosion rate with nickel content in the Fe-Ni-Cr system with the molten KHSO_4 electrolytes. It is clear that the corrosion resistance decreases with increasing nickel content. This is shown in Figure 7. Based on these results, nickel alloys have been deleted from future consideration. This data corroborates a prior AVCO conclusion. Fourth, corrosion rates in molten KHSO_4 give a much better correlation with AVCO Mark VII erosion losses than the aqueous K_2SO_4 results. This is shown in Figure 8.

Recognizing that post-test characterization of these test materials has not yet been completed, detailed interpretation is difficult. It appears that the iron (iron-chromium) based alloys form protective, somewhat resistive oxides. The Haynes 150 alloy evidently forms a similar oxide. It should be noted that Haynes 6B is not resistant to attack by KHSO_4 . This would indicate that tungsten and molybdenum additions to these alloys are detrimental to their corrosion resistance. A similar effect has previously been observed in the hot corrosion of super alloys by Na_2SO_4 melts.

Figure 6. Anode-Cathode Voltage Drops for Several Stainless Steel Alloys as a Function of Test Duration in Molten KHSO_4 at 300°C

Figure 7. Electrochemical Corrosion Rates of Fe-Ni-Cr Alloys (where $\text{Cr} \approx 18-30\%$) in Molten KHSO_4 as a Function of Alloy Nickel Content

Figure 8. Correlation Between Electrochemical Test and Mark VII (AVCO) MHD Generator Tests

In summary, the electrochemical corrosion of a series of commercial stainless steels and superalloys has been measured in both aqueous K_2SO_4 solutions and in molten $KHSO_4$. Heywood and Womack have suggested that the aqueous K_2SO_4 corrosion test (which is experimentally a very simple test) could serve as a means of predicting the erosion rates of metals in MHD generators. However, the Heywood and Womack correlation was based upon test results in both K_2SO_4 and K_2CO_3 solutions and were weighted heavily on platinum and copper data. By placing the emphasis upon high temperature alloy data and by using simulated coal-fired high sulfur tests it can be seen from Figure 9 that use of the aqueous K_2SO_4 test data to predict generator erosion rates is tenuous.

On the other hand, similar measurements using the molten $KHSO_4$ electrolyte did provide a good prediction of erosion resistance in the Mark VII generator. This can be rationalized on the following basis; $KHSO_4$ is a member of a family of potassium sulfate compounds that in the molten state are characterized as oxyanionic melts. Corrosion by molten $KHSO_4$ can be treated as hot corrosion at a relatively low temperature. Hot corrosion resistance is provided by the formation of oxide layers; these oxide layers must be resistant to spalling and should not be soluble in the liquid sulfate melt. As temperature is increased, any changes in the relative corrosion resistance between alloys is dependent upon changes in oxide scale formation, resistance to spalling and melt solubility. The correlation of the laboratory molten $KHSO_4$ results with generator results indicates that similar electrochemical reactions are occurring in both tests. Experiments using $K_2S_2O_7$ at $500^\circ C$ and K_2SO_4 at $1100^\circ C$ plus materials analysis should provide a clearer understanding of these reactions. Figure 9, which is based upon the British work (References 8 and 9), shows the effect of sample temperature upon corrosion rate in these melts. The current acceptance criteria for alloys, based on the $KHSO_4$ tests, is corrosion rates less than $10 \mu g/C$. This acceptance criteria will be refined when a correlation can be established between laboratory screening tests, WESTF tests and generator tests.

Experiments to be conducted in the next quarter will determine the temperature dependence of their corrosion rates. Because of the poor correlation with aqueous K_2SO_4 electrolytes no future tests are planned using these solutions.

Figure 9. Electrolytic Corrosion of Various Metals in Molten Potassium Sulfate Compounds

1.2.2 Anode Arc Erosion Tests

At the close of the prior quarter, some difficulty was experienced in achieving satisfactory anode arc erosion test reproducibility for a series of tests on 304SS specimens (Reference 1). A series of laboratory studies have been completed which were directed towards achieving satisfactory reproducibility for this laboratory screening test. It was suspected that the non-reproducibility was due to the differences in the apparent (measured) and real sample temperatures. It was also suspected that variations in the power of the arc due to small instabilities in the arc generator (or line voltage) and/or changes in the electrode in the arc generator may be contributing factors in the variability of the test results.

As a result of laboratory studies completed this quarter, which investigated the above effects, a modified test setup has been defined which has resulted in the desired degree of reproducibility. The emphasis in these investigations was to reduce the number of variables which could impact the test reproducibility. The significant changes incorporated in the test setup are as follows:

- addition of a constant current power supply in the arc generator circuit;
- deletion of the oxy-acetylene torch;
- deletion of the magnetic arc controller, and
- use of an improved thermocouple attachment technique.

First, the addition of the constant current power supply in the arc generator circuit minimizes variations in the arc power which could impact localized material temperatures. This insures that the arc current remains constant over the test period regardless of line power fluctuations or surface roughness variations or temperature variations of the sample. Second, the use of the oxy-acetylene torch to heat the surface of the sample to aid in establishing the temperature level has been eliminated. It was demonstrated that the arc, operating at the desired 5.5 amps, would readily heat the samples to the

desired temperature level of 500°C. Therefore, the use of an auxiliary flame is not only redundant, but, could potentially be a source of variability. Third, the use of a magnetic arc controller (MAC) to deflect the arc was also dropped from the test. Although the MAC expedited arc motion which was desirable, it also tended to destabilize the arc column causing it to become more diffuse and even in some cases to break up into multiple arcs. The inability to completely control arc morphology, when using the MAC, was suspected of being a factor in the non-reproducibility of the test. Fourth and perhaps most importantly, the method of attaching the thermocouple to the test sample was improved. Previously, the thermocouple was simply cemented with a high temperature ceramic bonding agent into a well on the back face of the test button. Post-test examination revealed that in many cases, physical contact between the thermocouple bend and the sample was lost leading to erroneous indicated temperatures. This most significant source of variability in the arc test has been rectified by the new practice of spot welding the thermocouple directly to the test sample. As part of the studies on test variability it was shown that varying the arc generator electrode tip angle, between 30° and 60° did not impact the test results.

The present anode arc test setup, schematically shown in Figure 10, incorporates all of the above modifications. With this new setup for the anode arc erosion test, sample surface temperatures are easily maintained at a constant temperature of 375°C or 500°C by air cooling the backface while a 5.5 ampere, 25-35 volt arc impinges on the sample for a one hour test period. The sample is rotated at 1 RPM and dry KHSO₄ is dusted in the surface at a rate of 0.1 gm every 2 minutes while reaction products are removed at 15 minute intervals.

Excellent reproducibility has been achieved with this new procedure. For example, four separate runs with solid SS-304 test buttons gave corrosion losses in Mg/coulomb of 16.1, 14.9, 15.6 and 14.7. These tests were run over a three week period and no time dependent drift in results were noted.

Referring to Table 3, Section IV-1.1, essentially all of the AVCO Alloys and Commercial Alloys had been tested using the prior anode arc erosion test setup. Since we cannot confidently identify which of these results were not subject to

Figure 10. Schematic of Anode Arc Test

the variability of the prior setup and since a slight difference in results are expected using the new test setup, these prior tests are being repeated. The status of the anode arc erosion test indicated in Table 4 is that based on the new setup described above. Initial results are given in Figure 11. Reflecting the limited testing completed using the new test setup, EB 26-1 demonstrates the most arc erosion resistance. This agrees with the results which had been obtained previously however, there is a difference in the absolute value of the corrosion loss.

Future tests will focus on those materials that show superior performance based on the electrochemical corrosion tests and on correlating the results of the arc test with available AVCO generator test results on these materials.

1.3 WBS 1.1.3 - Fabrication Development

Fabrication of Advanced Alloys, non-commercial, had been anticipated to begin during the latter part of this quarter. However, the start of actual fabrication activities has been deferred to the next quarter so that the identification of the specific alloys to be fabricated would benefit from the on-going laboratory screening test results.

A total of 17 material compositions have been identified and are listed in Table 5. These alloys reflect the deletion of nickel based alloys, see Section IV-1.2, and the resulting emphasis to be put on iron-chromium and cobalt-chromium based alloys. A number of variations are also planned to investigate the effect of small additions of platinum on the corrosion resistance of these binary alloys.

Additions and deletions to this list of materials are likely, based on future results from the laboratory screening tests. Raw material for these alloys is being procured and fabrication will begin next quarter. Vacuum arc melting and vacuum levitation melting techniques will be used in the fabrication of these Advanced Alloys.

Figure 11. Anode Arc Erosion of Several Alloys (KHSO_4 Corrodent)

2.0 WBS 1.2 - ENGINEERING TESTS

Table 7 provides an updated summary of those WESTF tests which have been planned for the period immediately following completion of facility activation activities which are currently in process. This summary identifies specific test materials as well as the specified operating conditions for the initial planned WESTF tests and indicates those areas where detailed revision have been defined since the prior quarterly report (Reference 1). Further details applicable to these tests, and other support activities, are presented in the following sections.

2.1 WBS 1.2.1 - Test Engineering

2.1.1 Development Requirements

General objectives associated with the initial 7 WESTF tests to be completed following magnet installation, WESTF Test 50 through WESTF Test 56, are as follows:

- to provide erosion rate data for copper to permit verification of a correlation between WESTF test results and generator test results (data will be obtained at three sulfur levels to permit correlation with existing AVCO data);
- to provide erosion rate data for platinum clad copper at the high sulfur level, 0.37 w/o sulfur in the plasma, for comparison with similar generator data;
- to provide for a limited investigation of the effect of magnetic field strength and electrode/slag interface temperature on the erosion rate of copper;
- to initiate screening of alternative cladding materials in parallel with ongoing laboratory screening tests, and
- to continue the evaluation of hafnia based materials, to be supplied by Battelle Pacific Northwest Laboratory, under super-hot operating conditions.

Test Specifications had been issued for WESTF Tests 50 through 54. Of these WESTF Tests 50 and 53 are part of the WESTF-generator correlation test series.

TABLE 7. SUMMARY OF PLANNED WESTF TESTS

REVISION AS OF 12/30/80

TEST ID	50	51	52	53	54	
Operating Mode	Cold	Cold	Super-Hot	Cold	Super-Hot	
Test Section	WESTF	MTS	MTS	WESTF	MTS	
Electrode Material ⁽¹⁾ (2)	(+) Cu (16) (-) W-Cu (8) (-) Cu (8)	(+) IN 671 (1) (+) EB 26-1 (1) (+) TiB ₂ (1) (+) 304 SS (1)* (-) W-Cu (4) * RUN 2 (+) 310 SS (1)* (+) EB 29-4 (1)* (+) FeCrAlY (1)* (+) Haynes 150 *	(+) A-LLL (2) ⁽³⁾ (+) A-MMM (2) (-) A-LLL (2) (-) B-MMM (2)	(+) Cu (2) (+) Pt. (4) ⁽⁴⁾ (+) HAYNES 150 (2) (+) IN 671 (2) (+) EB 26-1 (2) (+) EB 29-4 (2) (+) 310SS (2) (-) W-Cu (16)	(+) A-LLL (4) ⁽³⁾ (-) B-MMM (1) (-) A-LLL (3)	
Insulator Material	BN	BN	MgO	BN	MgO	
T _E , °C	125 & 275	~ 150	1600*	~225*	TBD*	
J, amp/cm ²	1.0	1.0	0.75 & 1.0	1.0	1.0	
Q, w/cm ²	~125	~125	~60	~125	~60	
B, Tesla	0 & 3	0	0	3	0	
Ash/Seed Type	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	Rosebud/K ₂ CO ₃	
Sulfur, w/o	0.05	0.14	0.14*	0.14*	0.14*	
Duration-Hrs.	~20	~20	10-20	~20	10-20	

- (1) ANODE AND CATHODE UNLESS OTHERWISE NOTED.
 (2) BRACKETS DEFINE NUMBER OF ELECTRODES
 (3) HAFNIA BASED MATERIALS SUPPLIED BY RPML.
 (4) AVCO REFERENCE ELECTRODES.
 (5) *DENOTES CHANGE INCORPORATED IN THIS ISSUE.

During this quarter, changes have been made to these test specifications to effect the following:

- WESTF Test 50, Final Test Specification - Revision 1
 - restated Test Objectives consistent with WESTF-Generator Correlation Verification Plan.
 - specified pre- and post-test measurements.
 - specified T/C's to be installed in 4 of 16 anodes to aid in monitoring test operations.
- WESTF Test 51, Final Test Specification
 - added Run 2 which is contingent on satisfactory demonstration of in-situ anode insert replacement. Run 2 anode clad materials selected based on results of laboratory screening test results.
 - Cu cathodes replaced by W-Cu clad Cu to extend cathode life-time for WESTF Test 51 Run 1 plus Run 2.
 - specified pre- and post-test measurements.
 - specified T/C's to be installed in each of 4 anodes to aid in monitoring test operations.
- WESTF Test 52, Final Test Specification
 - redefined electrode/interface design point to be consistent with available specimen thicknesses and allowable attachment maximum operating temperature (see discussion in Section IV-2.1.2, below).
 - specified T/C's to be installed in each specimen, anodes and cathodes.
 - increased sulfur level from 0.05 w/o to 0.14 w/o.
- WESTF Test 54, Preliminary Test Specification
 - increased sulfur level from 0.05 w/o to 0.14 w/o.
 - electrode surface/leadout interface/attachment interface temperatures are TBD (see discussion in Section IV-2.1.2, below).

2.1.2 Experiment Design

The following sections summarize thermal analyses completed in support of the detailed design of specific WESTF tests, as well as results of thermal analyses completed for the basic design of the MTS Test Section, hot wall version. Based on difficulties encountered in the final assembly of the WESTF test section for WESTF Test 50, a number of design changes have been defined for incorporation in the next build of a WESTF Test Section, i.e., for WESTF Test 53. Discussions are also presented on a profilometer system to be used in evaluating material loss during WESTF tests.

MTS Test Section

Detailed thermal analyses were completed in support of the hot version of the MTS test section to be used initially for WESTF Tests 52 and 54 (analyses in support of the electrode design are reported separately in the sub-section covering WESTF Tests 52 and 54).

The general configuration of the hot version of the MTS Test Section is shown in Figure 12; it differs from that previously presented (Reference 3) in that a composite structure, spinel brick faced with Norton MgO, is used on the electrode wall instead of a single layer of Norton MgO. The lower thermal conductivity of the spinel brick, when compared to high density Norton MgO, reduces the thickness of material required on the insulating wall and hence the overall size of the test section. Use of the Norton MgO as a facing material has been continued to minimize the potential for contamination of the electrode sample by adjacent materials. A castable refractory insulation is still used on the non-electrode walls of the hot version of the MTS Test Section.

The basic test section was designed to achieve a wall/plasma surface temperature of 1670°C which represents a compromise reflecting the desired electrode surface temperatures for WESTF Tests 52 and 54 of $\sim 1600^{\circ}\text{C}$ and 1700°C , respectively. Under non-slagging super-hot operating conditions, the radiant heat transfer from the walls of the test section is significant in terms of the thermal design of the electrode test specimens. Using a stainless shell, critical dimensions and operating temperatures for the test section are summarized in Table 8. One

Figure 12. MTS Test Section - Hot Version

TABLE 8. THERMAL CHARACTERISTICS OF HOT MTS TEST SECTION

Electrode Walls:

Liner Material	Norton MgO, t = 0.25 in.
Liner Surface Temperature	1670°C
Sub-Liner Material	Spinel Brick, t = 0.223 in.
Liner/Sub-Liner Interface Temp.	1048°C
Shell Material	304 SS, t = 0.88 in.
Coolant Channel Depth to Q_L	0.50 in.
Coolant Channel Diameter, in.	0.375 in.
Shell/Sub-Liner Interface Temp.	75°C

Insulating Walls:

Liner Material	Permanente 165, t = 0.506 in.
Liner Surface Temperature	1670°C
Shell Material	304 SS, t = 0.75 in.
Coolant Channel Depth, to Q_L	0.394 in.
Coolant Channel Diameter	0.250 in.
Shell/Liner Interface Temp.	101°C

other significant change was incorporated in the final design of the hot version of the MTS Test Section. Instead of using parallel coolant channels on the walls, a single flow path has been defined for each of the walls. This is illustrated in Figure 13.

Thermal Analysis - Slagging Cold Electrodes

Parametric thermal analyses were completed to determine the effect of a cladding of arbitrary material might have on the surface temperature of a copper electrode during equilibrium slagging conditions. Results of these analyses will be used to determine the increase in electrode surface temperature relative to that of a bare copper electrode when operated in either the WESTF or MTS test sections.

Assuming one dimensional heat transfer, the change in surface temperature caused by replacing a portion of the copper by an equal thickness of cladding is given by

$$\Delta T_s = \chi_c h_p (\dot{m}_p, T_p) [T_p - T_D] \left[\frac{1}{k_c} - \frac{1}{k} \right],$$

where

ΔT_s = change in surface temperature,

χ_c = thickness of cladding,

h_p = plasma heat transfer coefficient

$\dot{m}_p$ = plasma mass flow rate,

T_p = plasma temperature,

T_D = slag dew point,

k_c = thermal conductivity of the cladding,

k = thermal conductivity of copper.

The derivation of the above equation is predicated on two key assumptions. The first assumption is that equilibrium slagging conditions prevail so that the heat flow into the electrode is governed only by the difference between the plasma temperature and the slag dew point. Second, it is assumed that the introduction of the cladding does not seriously alter the mode of heat transfer

Figure 13. MTS Coolant Channel Schematic

to the water cooling the electrode, e.g., causing a drastic change in the film coefficient or causing boiling where previously, none occurred.

The analysis was conducted using a fixed cladding thickness, treating the thermal conductivity of the cladding and the plasma flow rate as the principal variables.

The thermal conductivity of the cladding was taken to vary to 8.7 W/m K. The plasma mass flow rate, which enters the analysis through the heat transfer coefficient, was taken at three levels, viz. 200, 250 and 300 gm/sec; the corresponding heat transfer coefficients are, respectively, 814.9, 982.4 and 1155.6 W/m² K (Reference 11).

The specific values for the fixed parameters employed in the study are as follows:

$$T_p = 2550 \text{ K,}$$

$$T_D = 1673 \text{ K,}$$

$$X_c = 0.060 \text{ inch,}$$

$$k = 394.6 \text{ W/m K (Copper)}$$

The results of the analysis are shown in Figure 14 over the rapidly changing region at the lower thermal conductivities which is the region of primary interest.

There are two attributes of the function for ΔT_s which allow one to extend Figure 14 beyond the immediate scope of this analysis. First, the function is linearly dependent on the cladding thickness. Thus, the figures can be applied exactly to any cladding thickness by multiplying ΔT_s by $X_c/0.060$, where X_c is the thickness of interest, measured in inches.

Second, there is no requirement in the derivation of the function that the substitute material (i.e., the cladding) be at the surface. Thus, Figure 14 is applicable to an equal thickness of substitute material placed at, or anywhere between, the plasma surface and the cooling channel(s).

Figure 14. Effect of 0.060 Inch Clad on Surface Temperature of Copper Electrode, Equilibrium Slagging Conditions

Finally, it should be noted that the function for ΔT_s is independent of specific geometry. Thus, Figure 14 applies equally for the electrodes in the MTS and WESTF configurations.

WESTF Tests 52 and 54

The desired operating conditions for the BPNL hafnia based electrode materials were initially defined as presented in Table 9. BPNL has provided electrode/leadout blanks for use in these tests and identified copper mesh as the preferred attachment for use with these materials. Use of nickel mesh was identified as a secondary attachment technique. In parallel with the detail thermal analyses, BPNL identified the maximum operating limits for the attachments as follows (Reference 13):

- Cu mesh 150°C
- Ni mesh 350°C, 300°C preferred.

The original electrode test conditions, see Table 9, could not be achieved when constrained by both the existing material thickness and the maximum leadout/mesh interface temperature. It was therefore necessary to redefine the test conditions/attachment to be compatible with the existing ceramic blank thicknesses.

The revised electrode test conditions are shown in Table 10 and are compatible with the characteristics of the BPNL electrode/leadout materials and attachment technique. Copper mesh is used for WESTF Test 52; nickel mesh is used for WESTF Test 54. In order to achieve the test conditions for WESTF Test 54 it will be necessary to increase the facility mass flow rate from 0.22 kg/sec, for WESTF Test 52, to 0.25 kg/sec.

WESTF Tests 52 and 54 will employ the MTS Test Section, hot wall version, previously described. The resulting electrode configurations are defined in Figure 15 and Table 11. General parameters applicable to these analyses are as follows:

TABLE 9. ORIGINAL TEST CONDITIONS, WESTF TESTS 52 AND 54

ELECTRODE PAIR	ELECTRODE- CURRENT LEADOUT MATERIAL	CURRENT DENSITY A/cm ²	ELECTRODE SURFACE TEMPERATURE °C nom.	ELECTRODE/LEADOUT INTERFACE TEMPERATURE °C $\pm$ 50
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WESTF TEST 52

A-1	A-LLL	0.75	1730	1180
C-1	A-LLL	0.75	1730	1180
A-2	A-LLL	1.00	1730	1180
C-2	A-LLL	1.00	1730	1180
A-3	B-MMM	1.00	1730	1180
C-3	B-MMM	1.00	1730	1180
A-4	B-MMM	0.75	1730	1180
C-4	B-MMM	0.75	1730	1180

WESTF TEST 54

A-1	A-LLL	1.00	1730	1100
C-1	B-MMM	1.00	1730	1100
A-1	A-LLL	1.00	1730	1300
C-2	A-LLL	1.00	1730	1300
A-3	A-LLL	1.00	1600	1200
C-3	A-LLL	1.00	1600	1200
A-4	A-LLL	1.00	1600	1300
C-4	A-LLL	1.00	1600	1300

TABLE 10. REVISED TEST CONDITIONS, WESTF TESTS 52 AND 54

ELECTRODE PAIR	ELECTRODE- CURRENT LEADOUT MATERIAL	CURRENT DENSITY A/cm ²	ELECTRODE SURFACE TEMPERATURE °C nom.	ELECTRODE/LEADOUT INTERFACE TEMPERATURE °C $\pm$ 50
<u>WESTF TEST 52</u>				
A-1	A-LLL	0.75	1600	1050
C-1	A-LLL	0.75	1600	1050
A-2	A-LLL	1.00	1600	1050
C-2	A-LLL	1.00	1600	1050
A-3	B-MMM	1.00	1600	1050
C-3	B-MMM	1.00	1600	1050
A-4	B-MMM	0.75	1600	1050
C-4	B-MMM	0.75	1600	1050
<u>WESTF TEST 54</u>				
A-1	A-LLL	1.00	1700	1000
C-1	B-MMM	1.00	1700	1000
A-2	A-LLL	1.00	1700	1000
C-2	A-LLL	1.00	1700	1000
A-3	A-LLL	1.00	1700	1000
C-3	A-LLL	1.00	1700	1000
A-4	A-LLL	1.00	1700	1000
C-4	A-LLL	1.00	1700	1000

1. ELECTRODE SEGMENT
2. LEAD-OUT SEGMENT
3. MESH
4. WATER JACKET
5. PRIMARY INSULATOR

Figure 15. Electrode Configuration, WESTF Tests 52 and 54

TABLE 11. ELECTRODE SIZES, WESTF TESTS 52 AND 54

WESTF TEST 52

POS.	MAT.	DIMENSIONS					Heat Flux ₂ w/cm ²	TEMPERATURE (°C)			
		X _E	X _L	X _m	X _j	X _i		T _E	T _L	T _m	T _j
A-1	A-LLL	0.160	0.527	0.158	0.795	0.955	60	1600	1050	125	33
C-1	A-LLL	0.160	0.527	0.158	0.795	0.955	60	1600	1050	125	33
A-2	A-LLL	0.160	0.527	0.158	0.795	0.955	60	1600	1050	125	33
C-2	A-LLL	0.160	0.527	0.158	0.795	0.955	60	1600	1050	125	33
A-3	B-MMM	0.166	0.445	0.158	0.795	0.874	60	1600	1050	125	33
C-3	B-MMM	0.166	0.445	0.158	0.795	0.874	60	1600	1050	125	33
A-4	B-MMM	0.166	0.445	0.158	0.795	0.874	60	1600	1050	125	33
C-4	B-MMM	0.166	0.445	0.158	0.795	0.874	60	1600	1050	125	33

WESTF TEST 54

POS.	MAT.	DIMENSIONS					Heat Flux ₂ w/cm ²	TEMPERATURE (°C)			
		X _E	X _L	X _m	X _j	X _i		T _E	T _L	T _m	T _j
A-1	A-LLL	0.259	0.625	0.170	0.795	1.133	47	1700	1000	137	30
C-1	B-MMM	0.269	0.526	0.170	0.795	1.041	47	1700	1000	137	30
A-2	A-LLL	0.259	0.625	0.170	0.795	1.133	47	1700	1000	137	30
C-2	A-LLL	0.259	0.625	0.170	0.795	1.133	47	1700	1000	137	30
A-3	A-LLL	0.259	0.625	0.170	0.795	1.133	47	1700	1000	137	30
C-3	A-LLL	0.259	0.625	0.170	0.795	1.135	47	1700	1000	137	30
A-4	A-LLL	0.259	0.625	0.170	0.795	1.133	47	1700	1000	137	30
C-4	A-LLL	0.159	0.625	0.170	8.795	1.133	47	1700	1000	137	30

● Plasma Mass Flow Rate	0.22 kg/s (WESTF Test 52) 0.25 kg/s (WESTF Test 54)
● Plasma Temperature	2550 K
● Wall Temperature (Test Section)	1670 ⁰ C (WESTF Test 52) 1700 ⁰ C (WESTF Test 54)
● Mesh	Cu (WESTF Test 52) Ni (WESTF Test 54)
● Mesh Conductivity	10.3 W/m K (Cu) 0.075 W/m K (Ni)
● Water Temperature	21 ⁰ C
● X_m	0.170 cm
● R_w	0.794 cm
● R_s	0.853 cm
● R_i	1.588 cm

WESTF Test Section Design Changes

The WESTF Test Section being assembled for WESTF Test 50, see Section IV-2.2 which follows, represents the first build-up of this new test section design. As a result of this experience, a number of design changes have been identified. It is expected that implementing these design changes will enhance the fabrication and assembly of the test section for WESTF Test 53. The primary areas of change, see Figure 16, include the following:

- ① Replace electrode to frame O-rings with formed-in-place gasket.
- ② Use of tubing compression fitting in lieu of hose clamps.
- ③ Reduction of electrode hose size from 3/8 inch to 5/16 inch or 1/4 inch.
- ④ Use of single piece peg wall elements.

Figure 16. WESTF Test Section Design Changes

- ⑤ Relocation of the G_L of the peg wall assembly to permit the addition of a sizable radius on the inside corner of the G-11 frame.
- ⑥ Use of welding in lieu of brazing for the fabrication of the coolant tube subassembly.

The background behind the most significant of these changes is discussed in the following paragraphs.

The most significant difficulty encountered in the fabrication and assembly of the test section for WESTF Test 50 has been in completing the tubing interconnections between the various elements of the frame hardware while satisfying leakage and envelope requirements. Space limitations combined with the cooling water pressure and temperature conditions severely limits the type of hose that can be employed. A nylon 11 hose was selected for use (Nylo-Seal by Imperial-Eastman); this hose possesses the most acceptable combination of strength, flexibility and minimum wall thickness, which are important characteristics for this particular application. It should be noted that space limitations also dictated the type of hose clamp that could be used. Figure 17 is a photograph of a portion of the test section for WESTF Test 50 which illustrates the spatial difficulties encountered. This figure also shows the Oetiker clamps which were used.

Satisfactory seals were achieved, however, with considerable difficulty. The Oetiker-type clamps proved very difficult to install in view of access limitations and considerable rework was required. The unyielding nature of the nylon tubing coupled with the limited clamping action of the Oetiker-type clamp resulted in a seal which could not be made consistently. An alternate sealing method, which is characterized by ease of installation, reliability, and minimum intrusion on available space, is required. Use of compression type fittings, when coupled with a reduction in tube size, should achieve this end. Flow data obtained during the checkout of the frames for WESTF Test 50 indicate that a reduction in tube size can be made without incurring unacceptable pressure losses. These fittings have been used elsewhere in the test section with very satisfactory results.

Figure 17. Tubing Connections, WESTF Test Section

The primary concern in this case, however, is that of space. This can best be illustrated by referring to Figure 18 which shows the overall test section configuration, for WESTF Test 50 and for WESTF Test 53. It is expected that the configuration of the test section for WESTF Test 53 is characteristic of the balance of the test sections that will be employed. The primary difference is that there are 16 electrode pairs within the magnet in the WESTF Test 53 configuration. As a result, supply and return tubing as well as electrical and instrumentation leads must be contained within the envelope established by the channel shaped shroud with 8 sets going in each direction. This is double that of WESTF Test 50 which has only 8 electrode pair within the magnet.

The peg wall cooling tube subassembly, see Figure 19, will be modified to use weld joints at positions A and B instead of braze joints as used in the test section for WESTF Test 50. The added strength associated with welded joints would be beneficial in accommodating misalignments encountered in the assembly of the peg wall assembly and its subsequent installation into the G-11 frame.

The other significant change is to substitute formed in place gaskets, at the electrode and peg wall to frame interfaces, for the O-ring originally specified. The formed in place gasket has been shown during the assembly of WESTF Test 50 to be simpler and more reliable than the use of O-rings.

Electrode Surface Profilometer

An important element of the evaluation of cold wall metallic materials is to determine the extent of material loss, including peak to average effects. For a number of anode clad materials, in particular platinum and future anticipated corrosion resistant materials, weight loss measurements cannot give data accurate or reliable enough to establish material loss rates. Further, weight measurements do not yield peak to average data.

To properly characterize these materials an accurate dimensional measurement technique would be more suitable. A system has been in use at the Semi-Conductor Division of Westinghouse to characterize the surface roughness of metal substrates. This system, shown in Figure 20, was used to measure the surface condition of a number of sample electrodes.

(A) WESTF TEST 50

(B) WESTF TEST 53

Figure 18. WESTF Test Section Configuration

A) Peg Wall Cooling Blocks

B) Cooling Tube Subassembly

C) Cooling Channel Extension

Figure 19. Components of WESTF Peg Wall Assembly

The system, schematically illustrated in Figure 21, includes the following:

- 1) Granite Surface Bed: A dimensionally flat surface for supporting electrode materials to be evaluated.
- 2) Slide Assembly: A series of slides (a motorized x-axis slide and a y & z-axis manual micrometer adjustable slide) for support and automatic tracing of a stylus across any desirable portion of an electrode surface.
- 3) Amplifier and Gauge Head: Electronically sensitive gauge head which supports the stylus that transmits a signal to the amplifier relating to the surface irregularity.
- 4) Strip Chart Recorder: Recorder which traces the produced surface irregularities transmitted by the amplifier on a 4" wide paper chart.

This profilometer system has the capability of measuring dimensional changes at full scale between 2.5-25 mils. The smallest accurate dimensional increment feasible is 0.05 mils, which is limited by the flatness of the granite bed and thickness of the stylus. With the capability of this instrument, dimensional mapping of the corrosion/erosion of MHD electrodes is easily accomplished.

Profilometer traces across the pitch and width of several WESTF Test 50 electrodes were made using the apparatus at the Semi-Conductor Division. The traces, as shown in Figure 22, represent the degree of surface roughness of both a copper and W-Cu clad electrode. From the traces there is observed up to 0.5 mil dimensional difference from end to end, obviously attributable to the limits of the machining operations. Profilometer traces across metallic samples exposed to a corrosive MHD environment are shown in Figure 23. This sample is bare copper anodes which were tested in WESTF Test 40. In addition, a trace has been shown for a typical anode arc test specimen.

This apparatus has the accuracy and sensitivity that is necessary in measuring electrode material losses, including loss distribution, and will be used in support of WESTF testing.

Figure 20. Profilometer Apparatus Used by Semi-Conductor Division of Westinghouse Electric

Figure 21. Schematic of Profilometer Apparatus

A) ANODE 2A2 (COPPER)

B) CATHODE 2C1 (W-Cu CLAD)

Figure 22. Typical Pre-Test Surface Profilometer Traces

(A) ANODE ARC TEST SPECIMEN - TRACE 1

(B) WESTF TEST 40 ANODE - TRACE 2

Figure 23. Typical Post-Test Profilometer Tracings

2.1.3 Post-Test Analysis

As previously reported, all post-test analysis activities associated with prior tests have been completed.

2.2 WBS 1.2.2 - Test Assembly Fabrication

WESTF Test 50 (WESTF Test Section)

All detail part fabrication activities have been completed as previously reported. Assembly of the entrance, transition, and exit sections, as well as the eight frames, has been completed. The entrance, transition, and exit section, as well as a typical frame, are shown in Figure 24. Final assembly of these sub-assemblies to form the full test section is in process.

The following activities have been completed as part of the assembly operations for WESTF Test 50:

- Pre-test dimensional data has been taken on all individual electrodes to form a basis for assessing material loss. On selected electrodes, profilometer measurements were taken using the setup previously described.
- Pre-test weight measurements have similarly been made for all electrodes.
- The coolant flow circuits of the final assembled frames have been leak checked at 100 psi. Each frame contains two parallel circuits; each circuit contains two electrodes and two peg wall assemblies.
- Flow characteristics of the cooling circuits have been measured. Results are presented in Table 12. These measurements indicate that a reduction in electrode cooling water tubing size, from 3/8 inch to 5/16 inch can be accommodated without incurring unacceptable pressure losses.
- Photographs have been taken of the hot face of each electrode to document surface condition for use in the post-test evaluation of the test. Typical photographs are shown in Figure 25.

Figure 24. WESTF Test 50 Hardware

TABLE 12. COOLANT CIRCUIT FLOW DATA, WESTF TEST 50

<u>Frame</u>	<u>Circuit</u>	<u>ΔP psi</u>	<u>Flow, gph</u>
1	1	100	53.2
	2	100	49.2
2	1	100	48.8
	2	100	50.5
3	1	100	52.4
	2	100	52.2
4	1	100	46.7
	2	100	46.9
5	1	100	48.6
	2	100	56.4
6	1	100	46.8
	2	100	49.9
7	1	100	51.6
	1	100	48.7
8	1	100	48.2
	2	100	48.8

Figure 25. Typical Electrode Surfaces, WESTF Test 50

Figures 26 and 27 show the sub-assemblies of the test section for WESTF Test 50 just prior to the start of final assembly. Figure 26 shows that portion of the total test section which will be external to the magnet; Figure 27 shows that portion which will be within the magnet.

WESTF Test 51 (MTS Test Section)

Machining of the specimen holders, inserts, is complete. Two sets are being provided in anticipation of two separate runs. Final machining of the test section walls is in process.

WESTF Test 52 (MTS Test Section)

Machining of the specimen holders, inserts, is complete. Machining of the test section walls has not yet been initiated.

WESTF Test 53 (WESTF Test Section)

Machining of the entrance, transition and exit sections has been completed. Fabrication of individual frame hardware is on hold pending completion of definition of design changes previously discussed.

WESTF Test 54 (MTS Test Section)

Machining of specimen holders, inserts, in process. Basic test section walls from WESTF Test 52 will be used for this test.

3.0 WBS 1.3 - WESTF OPERATIONS

As previously reported, primary facility modifications associated with the addition of a conventional 3 Tesla magnet were completed during the prior quarter (Reference 1). During the October to December 1980 quarter, emphasis has been put on those subsystem checkout and facility activation activities which are required in preparation for the initial WESTF test with the modified and reworked facility.

Figure 26. Exploded View, WESTF Test 50

Figure 27. Exploded View, WESTF Test 50

The final modification to be completed was the installation of the guard fence around the flow train. This fence is removable and will be in place when the magnet is operable. The primary function of the fence is to protect personnel against inadvertent access to the high voltages associated with the magnet. The guard fence was also integrated into the magnet power supply interlock circuit.

The general sequence of operations to be completed during facility activation is as follows:

- Functional subsystem testing
- Warm flow test
- Hot flow test

The functional subsystem testing will insure the proper operation of individual subsystems including: fuel, air, oxygen, seed/ash, magnet power supply, magnet, load bank, data aquisition, cooling water (city and recirculating) and scrubber. As required subsystem checkout activities are completed the flow train, with the dummy test section installed, will be subjected to a warm flow test. This is essentially integrated combustion testing to an intermediate temperature level. The final series of tests are termed hot flow tests. In these tests the flow train will be operated to achieve rated conditions.

GENERAL

The data aquisition programs for the mini-computer have been updated to conform to the recently modified WESTF facility. The data aquisition system now accepts additional inputs such as cooling water system flow rates, seed flow and magnetic field intensity. These inputs are used to provide easily readable displays and printouts which instantaneously show the condition of the flow train and the test section, both thermally and electrically. Features have been included to indicate when test or operating parameters are approaching limiting conditions. The programs have also been modified to make them more universally applicable to future tests.

FUNCTIONAL SUBSYSTEM TESTS

Cooling Water System

During checkout of the cooling water systems, recirculating water and city water, flow rates were determined for the various cooling water circuits, see Figure 28. No difficulties were encountered with the city water portion of the cooling water system. Satisfactory operation of the recirculating water system was achieved with the pressure regulator set at 120 psig. Under these conditions, no leaks were detected and all tubing and fittings were adequate. The cooling water system was operated at this pressure level for subsequent warm flow tests.

A failure of the new recirculating water system pressure regulator was encountered when, as a part of the magnet system checkout, the pressure regulator was reset to 150 psig, which was within the rating of the regulator. Further details are presented below.

It should be noted that failure of the pressure regulator in early December precluded any further system activation testing, including magnet system checkout, until the replacement pressure regulator is received and can be installed in the water system. Receipt of the replacement regulator is anticipated in early January 1981.

Fuel System

Functional checkout of the fuel system identified that the new turbine meter which had been installed to extend system flow capability would not function satisfactorily. In general the control circuit required significant debugging. It was determined that the turbine meter which had been received was over-sized. The original turbine meter was reinstalled, 0.2 Kg/s maximum total mass flow, pending receipt of the correct turbine meter and system checkout operations were completed. No significant difficulties were encountered with the plumbing associated with the fuel system.

Figure 28. WESTF Cooling Water Subsystem Schematic

Air System

In activating the air system, which includes the preheater and compressors, a significant amount of time was expended in debugging the control circuits. This activity has been completed and the system certified to support combustion testing.

Oxygen System

Functional checkout of the oxygen system was completed. In addition to pressure checks, the system was purged to insure compliance with the critical cleaning requirements for this system. The system was demonstrated to be clean and, after minor debugging of the control circuits was completed, demonstrated satisfactory operation.

Scrubber System

Only minor maintenance was required to fully activate the scrubber system. The system is ready for use.

Magnet System

The power supply for the magnet and the associated protective circuits were tested under no-load conditions. The operation of the power supply and its protective circuits was satisfactory.

Checkout of the cooling circuits was completed at a supply pressure of 120 psig. At this pressure level, the water pressure at the entrance to the magnet coils was 110 psig. The minimum water flow for an individual cooling circuit of the magnet coil was 0.75 GPM. Under rated operating conditions it is anticipated that the incremental increase in cooling water temperature for this particular circuit would be about 50°C. In order to reduce this temperature increase, it was decided to operate the system at a supply pressure of 150 psig which was within the rating of the pressure regulator. After being reset, operations were resumed and the pressure regulator failed. The replacement regulator is expected in early January.

As soon as the new pressure regulator is installed checkout of the magnet system will be continued. During these operations magnetic field strengths will be mapped as the magnet is brought up to full power.

Load Bank and Channel Wiring

The basic circuit for loading a given electrode pair of the test section is shown in Figure 29. This circuit was duplicated 16 times in order to accommodate up to 16 electrode pairs in a given test section.

The wiring associated with these 16 circuits was checked by energizing each of the 16 power supplies individually and measuring the open-circuit voltages at the points used for making electrical connections to the test section. The wiring connections and the accuracy of the voltages observed on the DAS were checked at the same time by comparing the voltages observed at the voltmeters and the digital display at the DAS. No difficulties were encountered in completing this check and a satisfactory degree of accuracy was achieved.

The load bank wiring and the accuracy of current readings on the DAS were then checked by shorting out the connections to the test section and energizing the individual power supplies. By varying the resistance of the load bank, and the voltage output of the power supply, the load current could be varied from the milliampere range to the maximum rating of the power supply. By comparing readings taken using external ammeters with voltage readings of the DAS the accuracy was found to be satisfactory.

The circuit shown in Figure 29 has been modified from that previously reported (Reference 1) in that a 500 volt 25 ampere diode has been placed across the power supply to minimize the effects of AC transients produced by the MHD plasma. A shorting switch has also been provided to permit shorting out the power supply when operation in the MHD mode is desired, i.e., where the power supplies are not used to supplement the currents generated in the test section.

The 40 circuits which are used for monitoring the floating voltages of the insulating wall components were also checked out. These circuits are essentially

COMPONENTS

1. 50,000 OHMS $\pm$ 1%, 5 WATTS
2. TRIMPOT, 100 OHMS 1/2 WATT
3. 450 OHMS $\pm$ 1%, 5 WATTS
4. TYPE HA SHUNT, EMPRO, 50mV, 50 AMPS
5. TAPERED RHEOSTAT, 300 Ω MAX. CURRENT, 8A
6. 5 OHMS, 225 WATTS

Figure 29. Individual Electrode Pair Circuit for Operation of WESTF with Magnet

the left hand side of the circuit shown in Figure 29. Checkout was accomplished using the techniques described above and everything was shown to be satisfactory.

WARM FLOW TESTS

Upon completion of prerequisite subsystem checkout tests, warm flow tests were initiated using the dummy test section. These tests are essentially integrated combustion tests using all of the flow train systems except for the magnet system. A total of three tests were completed prior to the failure of the cooling water system pressure regulator. At that point further integrated flow train tests were precluded until the replacement regulator could be installed. In these tests, the system was operated to achieve an intermediate gas temperature of approximately 1400°C. No difficulties were encountered in completing these tests. Ignition of the combustor proved to be more efficient than previously experienced. In addition to demonstrating satisfactory integrated system operation, these tests provided valuable operator training with the modified facility and identified improvements which have been incorporated in the WESTF operating procedures.

HOT FLOW TESTS

Hot flow tests, which will demonstrate satisfactory system performance at rated conditions, will be initiated following completion of magnet system checkout operations. These tests will be run up to mass flow rates of 0.22 Kg/s with the fuel system turbine meter that is currently installed. Following receipt of the new turbine meter the upper limit on total mass flow rate will be determined. Hot flow tests are conducted with the dummy test section.

Upon satisfactory completion of the hot flow tests, WESTF tests will be initiated.

4.0 WBS 1.4 - WESTF/GENERATOR CORRELATION

Activities in support of this task will commence after WESTF activation has been completed and subsequent WESTF tests are completed.

As part of the overall test planning activity, a WESTF - Generator Correlation Verification Plan was developed.

The initial series of four cold metallic electrode tests using the WESTF test section, i.e. WESTF Tests 50, 53, 55 and 56, is directed towards establishing the correlation between WESTF and generator test results. The test conditions, and materials to be tested, are shown in Table 3. Depending upon tests results, additional tests may be required to complete this correlation of WESTF and generator test results. This series will provide the following minimum data:

- copper
 - erosion rate versus sulfur level (3 pts)
 - erosion rate versus surface temperature (2 pts)
 - erosion rate with and without B field
- platinum
 - erosion rate at a minimum of one sulfur level
 - erosion rate as a function of time up to a duration of 70 hours

The copper and platinum data will be used to complete the correlation with AVCO Mark VI and Mark VII generator results. Based upon AVCO Mark VII test data, normalizing for a higher sulfur level and assuming measurements are comparable to AVCO's in accuracy and certainty, it is believed that a good platinum erosion rate can be obtained with a cumulative test duration of 70 hours.

5.0 WBS 1.5 - PROJECT MANAGEMENT

The following required project documentation was prepared and issued during the reporting period:

- Monthly Report for September 1980
- Monthly Report for October 1980
- Monthly Report for November 1980
- Quarterly Report for July-September 1980
- Project Management Summary Baseline Report, October 1980 - Final Issue

V. SUMMARY PLANS NEXT REPORTING PERIOD

Summary plans covering significant activities during the next reporting period, January to March 1981, are presented below in accordance with the FY 81 WBS primary tasks.

WBS 1.1 - ELECTRODE AND INSULATOR MATERIALS

- Complete anode arc erosion and electrochemical corrosion testing of previously identified candidate anode clad materials.
- Update, if appropriate, the acceptance criteria applicable to the laboratory screening tests.
- Initiate fabrication development of advanced alloys.

WBS 1.2 - ENGINEERING TESTS

- Prepare, or update, and issue Test Specifications applicable to WESTF Tests 52 through 56.
- Complete design of WESTF Tests 53 through 55.
- Complete fabrication and assembly of test sections for WESTF Tests 50 (WESTF, cold), WESTF Test 51 (MTS, cold), WESTF 52 (MTS, super-hot), WESTF Test 53 (WESTF, cold), WESTF Test 54 (MTS, super-hot) and WESTF Test 55 (WESTF, cold).
- Complete post-test analysis of WESTF Test 50 through 52.
- Assemble and check-out profilometer system for evaluating anode material loss.

WBS 1.3 - WESTF OPERATIONS

- Complete magnet subsystem checkout.
- Complete WESTF activation.

- Complete WESTF Tests 50, 51 and 52.
- Receive and install WESTF data logger.
- Complete scrubber modification.

WBS 1.4 - WESTF GENERATOR CORRELATION

- Initiate compilation of WESTF test results as part of WESTF-generator correlation verification.

WBS 1.5 - PROJECT MANAGEMENT

- Issue monthly status reports.
- Issue October to December 1980 Quarterly Report.
- Continue overall project management function.
- Complete DOE program review.

VI. CONCLUSIONS

The electrochemical corrosion rates of 25 refractory metals were measured in aqueous potassium sulfate solutions at 80°C and in molten potassium bisulfate at 300°C. A comparison of results on several iron, nickel and chromium based alloys indicates that the molten potassium bisulfate results gave a much better correlation with erosion rates in the AVCO Mark VII generator. This indicates that electrochemical corrosion by molten potassium bisulfate is a large contributor to generator material loss. Molten potassium bisulfate test results also demonstrate that by increasing the nickel content in iron, nickel and chromium based alloys the corrosion rates also increase. In fact, to meet the test acceptance criteria of $10 \mu\text{g}/\text{C}$, the nickel content must be less than ten percent. The alloys which showed the most promise are those of the iron-chromium and cobalt-chromium binary based systems. Specific promising alloys include: 406SS, 446SS, EB 26-1, EB 26-1B, EB 29-4, FeCrAlY and Haynes 150. Pure iron and a tool steel containing 6 percent chromium both demonstrate excellent corrosion resistance; however, it is anticipated the corrosion resistance of these metals will deteriorate at slightly higher temperature levels. Finally these tests give a strong indication that alloying elements such as molybdenum and tungsten will degrade or compromise the corrosion resistance of these alloys.

Changes to the anode arc test have been defined to improve the reproducibility of this laboratory screening test. The elimination of the arc deflector and the oxy-acetylene torch and the use of an improved thermocouple attachment technique has reduced the number of test variables and data scatter. Repeat tests have been initiated using the modified test setup.

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