12

FG

E.M. 4790

DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER

Semi-Annual Technical Report for
Period Ending November 30, 1975

Submitted to ARPA in February, 1976

Principal Investigator:

C. Mole

C. [illegible] Mole, Manager
Superconducting Electric Machinery Systems
Phone (412) 256-3612

Sponsored by:

Advanced Research Projects Agency
ARPA Order No. 2174

This research was supported by the Advanced Research Projects Agency of the Department of Defense under Contract No. DAHC 15-72-C-0229.
Effective date of Contract 10 May 1972.
Contract expiration date 31 August, 1976.
Amount of contract - $2,368,670.

Westinghouse Electric Corporation
Electro-Mechanical Division
P.O. Box 217
Cheswick, PA 15024

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Advanced Research Projects Agency or the U. S. Government.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Westinghouse Electric Corporation
Electro-Mechanical Division
Cheswick Avenue, Cheswick, PA 15024

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
6
DESIGN AND DEVELOPMENT OF A SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER,

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
9
Semi-Annual Technical Rep[redacted]rt, for period ending Nove[redacted]r 30 [redacted]75,

5. AUTHOR(S) (First name, middle initial, last name)
Mole,C.J.; Arcella,F.G.; Berkey,E.; Boes,D.J.; Doshi,V.B.; Feranchak,R.A.; Haller,H.E.,III; Johnson,J.L.; Karpathy,S.A.; Keeton,A.R.; Litz,D.C.; McNab,I.R.; Moberly,L.E.; Mullan,E.; Reichner,P.; Stillwagon,R.E.; Taylor,O.S.; Tsu,T.C.; Ulke,A.; Wedman,L.N.; Witkowski,R.E.

6. REPORT DATE
11
Feb[redacted] [redacted]76

7a. TOTAL NO. OF PAGES
12
79p.

7b. NO. OF REFS
6

8a. CONTRACT OR GRANT NO.
15
DAHC 15-72-C-0229,

b. PROJECT NO.

c. ✓✓ ARPA Order-2174

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
14
EM-4790

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
10
Qualified requesters may obtain copies of this report from Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314

11. SUPPLEMENTARY NOTES
C. J. /Mole, F. G. /Arcella, E. /Berkey,
D. J. /Boes V. B. /Doshi

12. SPONSORING MILITARY ACTIVITY
Advanced Research Projects Agency
Department of Defense
1400 Wilson Blvd., Arlington, VA 22209

13. ABSTRACT

This program is for the research and development of a new mechanical power transmission concept: the segmented magnet homopolar torque converter. The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, lightweight low volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. This machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments.

In Phase I the technical problems were reviewed, the machine concepts were studied, and a detailed technical plan was evolved for the entire program. In Phase II, a reliable constant speed current collection system was developed and demonstrated in an actual segmented magnet homopolar generator (SEGMAG). The objective of Phase III is to extend the technology developed in Phase II for constant speed machines to the case of the torque converter which must operate at variable and reversing speeds.

The program places particular emphasis on the technology of advanced current collection systems for the reason this is essential for the success of the homopolar machine concept.

Phases I, II, and the initial Phase III effort were based on the use of liquid metal current collectors. In Phase III-A (Beginning July 1, 1975) work was redirected toward the use of a promising current collection concept utilizing a solid brush-gas-vapor additive system.

This report period encompasses the completion of Phase III, and the initiation of Phase III-A.

Unclassified
Security Classification

390 359

1B

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
alkali metals						
current collectors						
dc motor						
drive						
drive motor						
electric brushes						
electric drive						
electric machine						
homopolar						
liquid metals						
motor						
propulsion						
ship propulsion						
torque converter						

TABLE OF CONTENTS

Page

PART A INTRODUCTION AND SUMMARY. Ai

Section 1 INTRODUCTION. A1-1
1.0 GENERAL. A1-1
1.1 BACKGROUND A1-1
1.2 OBJECTIVES A1-1
1.2.1 Summary of Objectives A1-1
1.2.2 Summary of Technical Tasks. A1-2
1.2.2.1 Phase I (Completed 9 January, 1973). A1-2
1.2.2.2 Phase II (Completed 30 June 1974). . A1-3
1.2.2.3 Phase III Initial Investigation (Completed 30 June 1975) A1-4
1.2.2.4 Phase III-A - Solid Brush Current Collector Development for High Current Density Applications (Initiated July 1, 1975) A1-5

Section 2 SUMMARY OF CURRENT PROGRESS A2-1
2.0 GENERAL. A2-1
2.1 COMPLETION OF PHASE III INITIAL INVESTIGATION. . . . A2-1
2.1.1 Machine Design and Testing. A2-1
2.1.1.1 Segmented Magnet Homopolar Generator (SEGMAG) A2-1
2.1.1.2 GEC Machine. A2-2
2.1.1.3 Torque Converter A2-2
2.1.2 Application Studies A2-2
2.1.3 Current Collection Development. A2-2
2.1.4 Liquid Metal Support Systems. A2-2
2.1.5 Seal Studies. A2-2
2.2 PHASE III-A SOLID BRUSH CURRENT COLLECTOR DEVELOPMENT FOR HIGH CURRENT DENSITY APPLICATIONS A2-3
2.2.1 Current Collector Test Rigs A2-3
2.2.2 Current Collector Contact Material/Performance A2-3
2.2.3 Current Collector Mechanical Load System. . . A2-3
2.2.4 Current Collector Interface Cooling Systems . A2-3
2.2.5 Current Collector Gaseous Environment/Control A2-4
2.2.6 Application Studies A2-4

PART B COMPLETION OF THE PHASE III INITIAL INVESTIGATION . . . . . . Bi

Section 1 INTRODUCTION. B1-1
1.0 GENERAL. B1-1

Section 2 MACHINERY B2-1
2.1 SEGMENTED MAGNET HOMOPOLAR MACHINE (SEGMAG) WITH LIQUID METAL CURRENT COLLECTORS. B2-1
2.1.1 Objectives. B2-1
2.1.2 Prior and Related Work. B2-1
2.1.3 Current Progress. B2-5

Table of Contents (cont'd)

Page

2.2 GEC GENERATOR. B2-11
2.2.1 Objectives. B2-11
2.2.2 Prior and Related Work. B2-11
2.2.3 Current Progress. B2-14
2.3 SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER (SMHTC). B2-15
2.3.1 Objectives. B2-15
2.3.2 Prior and Related Work. B2-15
2.3.3 Current Progress. B2-16
2.4 REFERENCES B2-17

Section 3 APPLICATION STUDY B3-1
3.0 OBJECTIVES B3-1
3.1 CURRENT PROGRESS B3-1

Section 4 CURRENT COLLECTION SYSTEMS. B4-1
4.0 OBJECTIVES B4-1
4.1 CURRENT PROGRESS B4-1

Section 5 LIQUID METAL SUPPORT SYSTEMS. B5-1
5.0 OBJECTIVES B5-1
5.1 CURRENT PROGRESS B5-1

Section 6 SEAL STUDY. B6-1
6.0 OBJECTIVES B6-1
6.1 CURRENT PROGRESS B6-1

PART C PHASE III-A SOLID BRUSH CURRENT COLLECTOR DEVELOPMENT FOR HIGH CURRENT DENSITY APPLICATIONS Ci

Section 1 INTRODUCTION. C1-1
1.0 BACKGROUND C1-1
1.1 OBJECTIVES C1-1
1.2 PRIOR AND RELATED WORK C1-2

Section 2 CURRENT PROGRESS. C2-1
2.1 CURRENT COLLECTOR TEST RIGS. C2-1
2.1.1 Laboratory Brush Testers. C2-2
2.1.1.1 Objectives C2-2
2.1.1.2 Prior and Related Work C2-2
2.1.1.3 Current Progress C2-2
2.1.2 Machine-Environment Brush Tester (MEB). C2-8
2.1.2.1 Objectives C2-8
2.1.2.2 Prior and Related Work C2-8
2.1.2.3 Current Progress C2-8
2.2 CURRENT COLLECTOR CONTACT MATERIAL/PERFORMANCE . . . C2-14
2.2.1 Objectives. C2-14
2.2.2 Prior and Related Work. C2-14
2.2.3 Current Progress. C2-14

Table of Contents (cont'd) Page

2.2.3.1 Testing Procedure or Factors C2-15
2.2.3.2 High Current Density (500-2500 A/in^2) Brush Material Test Results . C2-16
2.2.3.3 Medium-High Current Density (to 500 A/in^2) Brush Material Test Results . C2-20
2.3 CURRENT COLLECTOR MECHANICAL LOAD SYSTEMS. C2-24
2.3.1 Objectives. C2-24
2.3.2 Prior and Related Work. C2-24
2.3.3 Current Progress. C2-24
2.4 CURRENT COLLECTOR INTERFACE COOLING SYSTEMS. C2-29
2.4.1 Objectives. C2-29
2.4.2 Prior and Related Work. C2-29
2.4.3 Current Progress. C2-29
2.5 CURRENT COLLECTOR GASEOUS ENVIRONMENT/CONTROL. . . . C2-31
2.5.1 Objectives. C2-31
2.5.2 Prior and Related Work. C2-31
2.5.3 Current Progress. C2-31
2.6 REFERENCES C2-33

Section 3 APPLICATION STUDIES C3-1
3.1 OBJECTIVES C3-1
3.2 PRIOR AND RELATED WORK C3-1
3.3 CURRENT PROGRESS C3-1

REFERENCES

References are listed at the end of each section.

LIST OF FIGURES

Figure Page

PART B

2.1.1 SEGMAG Generator - The current collector terminals are shown in the foreground. The leads to the excitation coils are on top. B2-3

2.1.2 SEGMAG Generator on its test stand - The drive system and gas purification system are both on the right. The six NaK purification and supply loops are below. To their right are the gas subsystems for intercollector pressure balancing and shaft sealing. B2-3

2.1.3A 5. ms/Division Sweep Rate. B2-9

2.1.3B 0.5 s/Division Sweep Rate. B2-9

2.1.3C 1.0 s/Division Sweep Rate. B2-9

2.2.1 GEC vertical shaft homopolar machine schematic. B2-13

PART C

2.1.1 Test Chamber of Type B1 Brush Tester. C2-3

2.1.2 Type B1 Brush Test System. C2-5

2.1.3 Physical Arrangement of Components of Type HS1 and HS2 High Speed Brush Testers. C2-7

2.1.4 High Speed Brush Testers (HS1 and HS2). C2-9

2.1.5 Machine-Environment Brush Tester (MEB). C2-11

2.2.1 Contact Voltage Drop vs Load Pressure for Various Brush Materials. C2-21

2.2.2 Friction Coefficient vs Load Pressure for Various Brush Materials. C2-22

2.3.1 Brushholder used in HS1 Brush Test Rig. C2-26

2.3.2 Brushholder Arrangement for the Machine-Environment Brush Tester (MEB). C2-27

2.5.1 Current collection gaseous environment control system for use with the Machine-Environment Brush Tester (MEB). C2-32

LIST OF TABLES

Table		Page
PART B		
2.1.1	Efficiency Tabulation	B2-5
PART C		
2.2.1	Silver-Graphite Material Brush Test Results	C2-17
2.2.2	Performance Characteristics of SG216(1) Material Brushes	C2-18
2.2.3	Performance Characteristics of Selected Metal-Graphite Material Brushes	C2-19
2.2.4	Performance Characteristics of Brush Materials (500 A/in^2) (Medium-High Current Density Applications)	C2-23

PART A

INTRODUCTION AND SUMMARY

PART A: INTRODUCTION AND SUMMARY

SECTION 1

INTRODUCTION

1.0 GENERAL

This is the seventh semi-annual technical report and covers the work performed from June 1, 1975 through November 30, 1975. During this period, Phase III workscope was completed and Phase III-A was initiated.

Part B of this report covers the completion of Phase III. Part C describes the work performed under Phase III-A.

1.1 BACKGROUND

This program is for the research and development of a Westinghouse-proposed mechanical power transmission concept: the segmented magnet homopolar torque converter (SMHTC). The purpose of this device is to convert unidirectional torque of constant speed (such as from a steam turbine prime mover) into variable speed output torque in either the forward or reverse directions. The concept offers an efficient, light-weight low-volume design with potential application over a wide range of speeds and power ratings in the range from hundreds to tens of thousands of horsepower. Initial analysis indicates that this machine concept can be applied to commercial and military advanced concept vehicles for both terrain and marine environments with considerable benefit to the U.S. Government, provided the complex current collection and materials problems can be solved.

The present contract is part of a proposed three phase program to develop the segmented magnet homopolar torque converter (SMHTC). This program will: a) solve the operational problems relating to current collection systems for segmented magnet machines; b) demonstrate the solution of these problems in small segmented magnet homopolar machines (SEGMAG); c) utilize the developed technology to design, construct and test a segmented magnet homopolar torque converter (SMHTC).

The program will place particular emphasis on the technology of advanced current collection systems for the reason that this is essential to the success of the homopolar machine concept for high power density applications.

1.2 OBJECTIVES

1.2.1 Summary of Objectives

In Phase I, completed on January 9, 1973, all of the technical problems were reviewed, the machinery concepts studied, and a detailed technical plan was evolved for Phase II.

Phase II had the primary purpose of providing the necessary theoretical and engineering design work, as well as the supporting experimental tasks, to develop a reliable and efficient liquid metal current collection system for the successful operation of a segmented magnet (SEGMAG) homopolar generator. Key task areas included: (a) the design, construction, and operation of a SEGMAG generator having sodium-potassium (NaK) current collectors and all necessary support systems for liquid metal handling and purification, cover gas purity maintenance, and shaft seals; and (b) the procurement and testing of a GEC Ltd. homopolar generator with its Gallium-Indium (GaIn) current collector system.

The objectives of Phase III are to extend the technology developed in Phase II for constant speed machines (such as generators) to the case of a torque converter which operates at low speed, zero speed, or reversing conditions and then to construct and test a demonstration machine.

Phases I, II, and the initial Phase III effort were based on the use of liquid metal current collectors. In Phase III-A (beginning July 1, 1975) work was redirected toward the use of a promising current collection concept utilizing a solid brush-gas-vapor-additive system.

1.2.2 Summary of Technical Tasks

1.2.2.1 Phase I (Completed 9 January, 1973)

The results of Phase I are described in the first and second semi-annual technical reports (EM 4471, December 1972, and EM 4518, June, 1973).

The technical subtasks for Phase I were described in detail in the first semi-annual technical report (E.M. 4471), and were as follows:

1) Segmented magnet homopolar torque converter (SMHTC) system studies.

2) Application study.

3) Liquid metal current collection systems.

4) Materials study.

5) Segmented magnet homopolar machine design.

6) Seal study.

7) Plan for phase II.

1.2.2.2 Phase II (Completed 30 June 1974)

The results of Phase II are described in the 2nd, 3rd, 4th and 5th semi-annual technical reports (EM 4518, June 1973; EM 4559, January 1974; EM 4602, July 1974; EM 4648, February 1975).

There were five major task areas under Phase II:

(1) Machine Design and Testing

Construct a 3000 HP segmented magnet homopolar machine in order to prove the SEGMAG concept and to provide a test vehicle for the liquid metal current collectors, seals, and materials which were developed under this program.

Obtain a homopolar generator from the General Electric Co. (GEC) of England in order to obtain operational experience with GaIn as a current collector liquid.

(2) Application Studies

Select the most useful applications for segmented magnet homopolar machines or torque converters.

(3) Current Collection Development

Evolve an effective liquid metal current collection system.

(4) Liquid Metal Support Systems

Develop and fabricate liquid metal and cover gas recirculation systems to protect the liquid metal in the current collectors.

Study the compatibility of all machine materials (insulation, lubricants and structural materials) with the liquid metal current collection fluid.

Conduct a fundamental study of liquid metal technology, including surface wetting, aerosol formation, corrosion reactions, effect of high currents, and chemistry control in liquid metals.

(5) Seal Study

Develop seal systems for unidirectional SEGMAG machines to: (a) confine the liquid metal to the collector zone; and (b) prevent air contamination of the liquid metal and loss of its protective cover gas atmosphere.

1.2.2.3 Phase III - Initial Investigation (Completed 30 June 1975)

The results of the initial Phase III workscope are contained in the 5th and 6th semi-annual technical reports (EM 4648, February 1975; EM 4705, July 1975), and in this present (7th) report.

The following task areas defined the initial Phase III workscope:

(1) Machine Design and Testing

SEGMAG demonstration machine development and testing will continue, with the objective of further increasing output power and refining current collector technology.

GEC machine performance will be studied to evaluate GaIn current collection technology.

Torque converter. A conceptual design will be evolved for a prototype torque converter suitable for a military application.

(2) Current Collection Development

The unidirectional SEGMAG current collectors of Phase II will be further refined and extended to higher speed applications. In addition, collectors suitable for reversible and variable speed applications will be investigated. The work falls into five categories:

a) SEGMAG Collectors (67 m/s speed), unidirectional constant speed.

b) High Speed Collectors (96 m/s), unidirectional constant speed.

c) Flooded Collectors, for reversing and variable speed, which offer the advantages of design simplicity, and ease of liquid metal containment.

d) Unflooded collectors, for reversing and variable speed, which have the highest efficiency, but difficult containment problems.

e) Hybrid collectors, for reversing and variable speed, which combine the advantages of liquid metal and solid brushes.

(3) Liquid Metal Support Systems

The SEGMAG liquid metal system will be further developed and simplified. Support systems will be developed for use in torque converter and motor applications where reversible and variable speeds are encountered. GaIn technology studies will be pursued with respect to machine requirements.

(4) Seal Studies

The seal technology of Phases I and II will be extended to higher speed unidirectional applications. In addition seals for reversible and variable speed applications will be developed, as required for motors and torque converters.

1.2.2.4 Phase III-A - Solid Brush Current Collector Development for High Current Density Applications (Initiated July 1, 1975)

During this continuation of Phase III, research efforts are being performed in current collection technology using a solid brush-gas-vapor-additive system for use in the torque converter. The work to be performed includes the following:

1. Using suitable parameters for typical machines, evaluate promising materials and atmospheres, in terms of velocity, current density, pressure, life, losses and voltage drop. Select suitable combinations for continued evaluation.

2. From the materials selected in Item 1 above, construct large brushes and test in the preferred atmosphere.

3. Construct a slip ring system using a suitable array of solid brush materials and test for bulk properties at variable speed. Evaluate load current sharing problems.

4. Determine the brush loading and cooling system requirements for selected materials. Evolve a system concept and fabricate a model for initial tests.

5. Design and construct a model system using two slip rings to evaluate the solid brush SEGMAG concept, and to determine the potential future technical problems with such a system. Test over a wide range of speeds and loadings.

6. Conduct a continuous application study to correlate brush research with machine requirements and potential utilization. Assist in materials selection.

The Phase III-A workscope has been categorized into the following subtasks which are further defined in Part C of this report:

1. Current Collector Test Rigs.
2. Current Collector Contact Material/Performance.
3. Current Collector Mechanical Load Systems.
4. Current Collector Interface Cooling Systems.
5. Current Collector Gaseous Environment/Control.

SECTION 2

SUMMARY OF CURRENT PROGRESS

2.0 GENERAL

Work during this reporting period involved two main categories: 1) A completion of previously-begun efforts on liquid metal current collection with the final testing of a 3000 HP SEGMAG generator with NaK current collectors, and 2) the beginning of an effort to develop solid brush current collection for high current density applications.

2.1 COMPLETION OF PHASE III INITIAL INVESTIGATION

2.1.1 Machine Design and Testing

2.1.1.1 Segmented Magnet Homopolar Generator (SEGMAG)

The experimental program for the liquid metal SEGMAG was completed. The last series of tests evaluated were:

- Contact resistance in the current collector
- Parasitic losses
- Pulse operation characteristics

The effect of current, collector temperature and time was investigated. The current collectors were nickel plated to enhance wetting. The results indicate the presence of contact resistance; however, it was not a strong function of the test parameters.

The air gap geometry in the SEGMAG was redesigned to reduce parasitic losses. Iron bars were inserted in the top of the stator slots to achieve uniformity in air gap flux. The results showed a decrease in parasitic losses from 10 KW to 6 KW.

The SEGMAG was pulsed from zero to 50,000 amps by pulsing the field coil. The armature current lagged the field current somewhat due to the solid iron in the magnetic circuit. If the machine were to be pulsed in this manner, laminated iron would be required to increase the armature response time. However, if the armature circuit were pulsed at constant field, the solid iron construction of SEGMAG would be acceptable.

As a result of testing, additional work is recommended to further evaluate the following areas:

- Current collector critical temperature

- Contact resistance
- Liquid metal purification
- Internal electrical insulation
- Expulsion forces on liquid metal

2.1.1.2 GEC Machine

This machine was satisfactorily evaluated in a previous report period (fifth semi-annual technical report E.M. 4648 dated February 1975), and will be used as a high-current source for the solid brush test rigs of Phase III-A.

2.1.1.3 Torque Converter

Work on this task was completed with an investigation into the means of controlling the torque converter. This study showed that a satisfactory control system is achievable.

2.1.2 Application Studies

Due to the redirection of the contractual scope from liquid metal to solid brush current collection, the application studies are reported under Phase III-A of this report. See Part A section 2.2.6 for a summary of this work.

2.1.3 Current Collection Development

Further pursuit of this task was terminated due to redirection of the contractual scope from liquid metal to solid brush current collection.

2.1.4 Liquid Metal Support Systems

Further pursuit of this task was terminated due to redirection of the contractual scope from liquid metal to solid brush current collection.

2.1.5 Seal Studies

Further pursuit of this task was terminated due to redirection of the contractual scope from liquid metal to solid brush current collection.

2.2 PHASE III-A SOLID BRUSH CURRENT COLLECTOR DEVELOPMENT FOR HIGH CURRENT DENSITY APPLICATIONS

2.2.1 Current Collector Test Rigs

Detailed descriptions of two laboratory slip ring-type brush testers are presented. One tester (B1) is for the evaluation of subsize brushes, and the other (HS1) for full-size brushes.

The Machine-Environment Brush Tester (MEB) presently under construction is described and will provide a means of evaluating current collection system performance at design speeds in an environment typical of SEGMAG machines. This test rig will be used to study current sharing in multiple brush systems, methods of current transfer from brush to holder, brush cooling, and brush actuation.

2.2.2 Current Collector Contact Material/Performance

A number of metal-graphite and electrographitic material brush grades were evaluated for high and medium-high current density applications.

One silver-graphite brush grade, SG216, showed best overall feasibility for the high current density application.

Performance at high current density appears to be affected by brush material processing, percent metal content in the brush, and possibly, percent ring coverage by brushes. Low friction and long life depend upon a humidified inert gas atmosphere and adequate cooling of the brush-ring interface.

Performance results of graphite grade W417 running in the medium-high current density range (to 500 A/in^2) were very encouraging. Extremely long brush life was projected and power losses are reasonably low.

2.2.3 Current Collector Mechanical Load System

Two test brush holder arrangements were designed for high current density brush testing. One of these brush holders was installed in the HS1 full-size brush tester and was utilized for several months in brush screening tests. The other brush holder is similar and will be incorporated into the Machine-Environment Brush Tester (MEB).

2.2.4 Current Collector Interface Cooling Systems

The brush holders were instrumented to determine the heat transfer characteristics of the high current density brushes. The full-size brush tester is currently being analyzed theoretically and empirically to determine the thermal resistance between the brush and the brush holder.

The Machine-Environment Brush Tester (MEB) was similarly instrumented so that its test results can be compared to the full-size brush tester. The heat transfer information is necessary to develop high current density brush holder design requirements and procedures.

2.2.5 Current Collector Gaseous Environment/Control

A recirculating gas system, designed to provide a controlled gaseous environment in the MEB machine was constructed. This system controls internal pressure, provides make-up gas, conditions gas with water vapor, measures moisture content of the gas stream into and out of the machine and filters impurities from the recirculated gas.

2.2.6 Application Studies

In order to guide the development efforts on solid brush current collectors and materials, the range of slip ring and commutator peripheral speeds was defined for both motors and generators. The range of operating and overload current levels was also considered as well as the effects of magnetic fields and vibration on the brush loading system.

PART B

COMPLETION OF THE PHASE III INITIAL INVESTIGATION

PART B: COMPLETION OF THE PHASE III INITIAL INVESTIGATION

SECTION 1

INTRODUCTION

1.0 GENERAL

The research work based on the use of liquid metal current collection, including the 3000 HP SEGMAG generator with NaK current collectors, was completed. Part B of the report gives the results obtained during this period related to the use of liquid metal current collectors, and prior to the initiation of Part C work on the development of solid brush current collectors.

SECTION 2

MACHINERY

2.1 SEGMENTED MAGNET HOMOPOLAR MACHINE (SEGMAG) WITH LIQUID METAL CURRENT COLLECTORS

2.1.1 Objectives

The objectives of this program are:

1) To demonstrate the technical and economic feasibility of the Segmented Magnet Homopolar Machine concept, which offers an efficient, lightweight, low volume design with potential applications over a wide range of speeds and power ratings.

2) To provide a test vehicle for evaluation of the liquid metal current collection systems, containment seals, and liquid metal handling systems developed in previous subassembly testings.

The demonstration SEGMAG unit (rated 3000 HP, 3600 RPM) will subject the current collectors to current densities, leakage flux and other conditions associated with operation in a machine environment. In addition, the unit will provide for long-term testing of current-collectors, their attendant support systems and the machine itself to develop operational data for liquid metal machines.

2.1.2 Prior and Related Work

The SEGMAG concept was developed to provide a high performance DC machine without requiring superconducting magnet excitation. This low reluctance machine, using room temperature excitation, has capability for high output per unit weight and volume. The modular construction allows for higher outputs by using many modules connected in series. The characteristics of this machine have been investigated thoroughly in another U.S. Government Contract (N000 14-72-C-0393).

The demonstration SEGMAG machine design was completed in January 1974. Fabrication of the machine was completed in May 1974. The machine was assembled and installed on the test stand in May 1974. Following connection of the subsystems, machine decontamination and system checkout, the machine technology test program was initiated. The initial portions of the test plan were executed successfully. These tests included slow speed rotor test to insure proper assembly and high speed machine test to develop the vibration signature of the SEGMAG. In addition, the machine friction and windage losses were determined as a function of machine speed.

After disassembly, inspection and minor modifications, the initial series of tests was continued for 140 hours of SEGMAG operation. Short-circuit output of 90,000 amperes and 19 volts open-circuit was achieved. The testing validated both the SEGMAG machine concept and the liquid metal current collector system.

Following the test run the machine was dissassembled and inspected. Decontamination was rapid and straightforward.

Several modifications were undertaken including:

- Insulation in the collector region to improve NaK containment.
- A strain gauge system on the rotor shaft to improve torque and power measurements.
- Changes in the air gap configuration to improve the machine performance.

After analysis of the data from the initial test series several minor changes were made as follows:

1) The air gap geometry was modified in order to reduce parasitic losses, and

2) The current collectors were silver plated to enhance wetting.

The machine was then assembled and installed on the test stand, and the second test series was initiated in early 1975.

The tests for friction, windage, and NaK viscous loss were repeated for comparison with previous measurements. Series open-circuit and short-circuit tests were then performed with these favorable results:

- Successful operation of SEGMAG and auxiliary machine systems at or near rated design conditions for extended periods. Total running time to date is 215 hours.
- Peak power demonstration of 107,000 amperes and 20.8 volts, corresponding to a rating of 2983 horsepower (versus a program target level of 3000 horsepower).
- Verification that steady state power levels of 90,000 amperes and 20 volts can be maintained, corresponding to a 2413 horsepower rating.

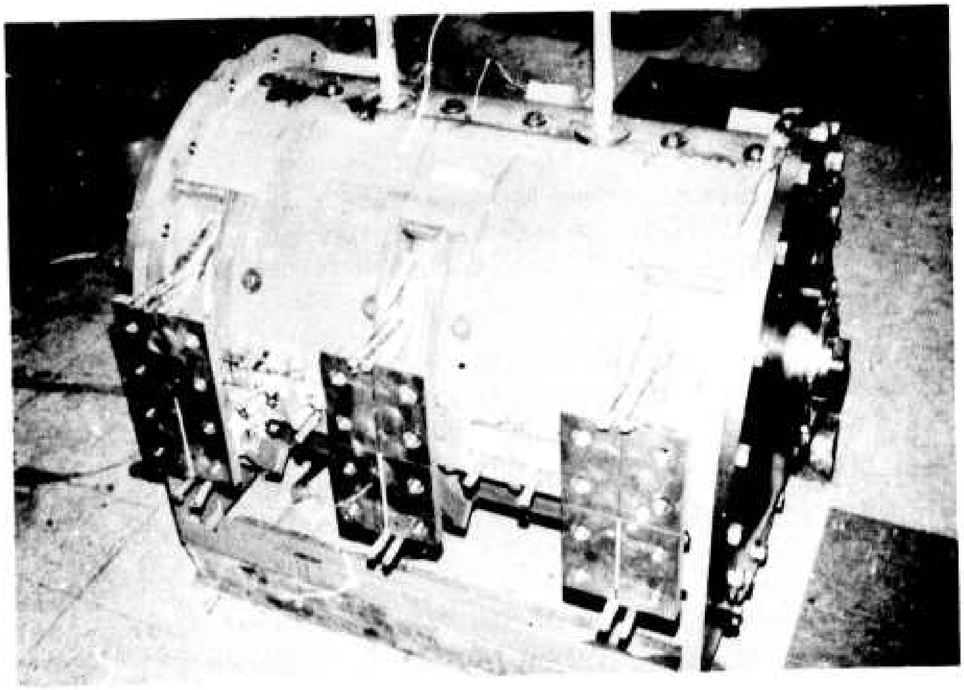


Fig. 2.1.1: SEGMAG Generator - The current collector terminals are shown in the foreground. The leads to the excitation coils are on top.

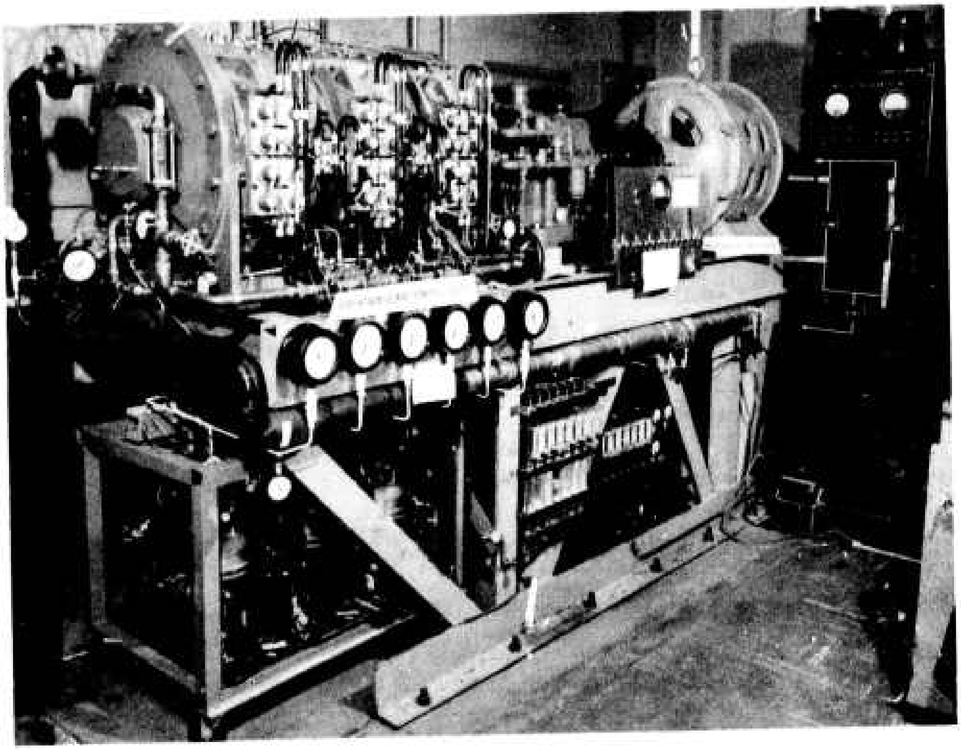


Fig. 2.1.2: SEGMAG Generator on its test stand - The drive system and gas purification system are both on the right. The six NaK purification and supply loops are below. To their right are the gas subsystems for intercollector pressure balancing and shaft sealing.

- Machine efficiency of 92.5%.
- Demonstration that these performance levels are primarily restricted by the capability of the present collector design to confine NaK against the magnetohydrodynamic ejection forces and to operate with low contact resistance.
- Identification of design improvements capable of producing 93,300 amperes at 30 volts (power rating = 3750 horsepower) with 97% efficiency within the volume of the present machine.
- Verification that the technology base developed earlier in the program could be successfully implemented in an operating machine.

Table 2.1.1 presents a summary of the losses observed during the open circuit, short circuit, and rotational tests of SEGMAG and compares them with, a) the original design objective, b) the test data obtained during the test program, and c) the capability of the present design with additional modifications.

The projected capability of the present SEGMAG machine after incorporating known modifications from the ongoing current collection technology program is given in column 3 of Table 2.1.1. The projected improvements will come mainly from:

- Reduction of current collector operating temperature.
- Elimination of stray losses.
- Reduction of viscous, magnetohydrodynamic, and contact resistance losses.

The test program has identified several areas that require further investigation. These are common to all homopolar machines using liquid metal current collectors including:

1) Current collector critical temperature.

2) Contact resistance.

3) Current collector performance.

4) Electrical insulation.

TABLE 2.1.1 - EFFICIENCY TABULATION

Design Loss, KW	Design Objective 3000HP	Test Run Data 20V, 90,000A 2400HP	Present Design Capability 24V, 93,300A 3000HP
Winding Joule	49.2	70.3	50.3
Collector	32.1	72.4	30.0
Mechanical Friction and Windage	2.6	2.0	2.0
Total, KW	83.9	144.7	82.3
Rating, KW	2240	1800.0	2240.0
Input, KW	2324	1945.0	2322.0
Efficiency, %	96.4%	92.5%	96.5%

Following the completion of this test series, SEGMAG was decontaminated and inspected. Several modifications were made in preparation for the next series of tests scheduled for mid-1975:

- Parasitic losses. The air gap was redesigned to increase the circumferential reluctance.
- Increased insulation was provided to prevent pinhole shorts in the machine bore.
- The collector surfaces were nickel plated to improve wetting of the NaK. Based upon the current collector work described in Section 4 of the previous semi-annual technical report (EM 4705), this should eliminate the need to heat the collectors prior to machine operation.

2.1.3 Current Progress

The final series in the Liquid Metal SEGMAG Test program was started on June 30, 1975. The objectives of this program included:

- Evaluation of the contact resistance phenomenon.
- Study of parasitic loss.

- Establishment of pulse load characteristics of SEGMAG.

The presence of a contact resistance in the collector can have a serious impact on the machine losses and expulsion forces as reported in the previous report (EM 4705). A test program was planned to determine the effect of various parameters on contact resistance. A review of previous test data indicated that the contact resistance was dependent upon three factors:

- Current collector temperature.
- Armature current.
- Time.

A series of tests were designed to estimate the effect of temperature, current and time on contact resistance using a statistical technique known as Factorial Design. Briefly, this technique involves a randomly selected series of tests in which each of the three parameters are set at two levels as follows:

Parameters	High	Low
Current Collector Temp. (°C)	100	70
Armature Current (KA)	60	40
Time (Min.)	90	30

These three parameters are listed in "standard order":

Standard Order	Temp. °C	Current KA	Time (min)
1	70	40	30
2	100	40	30
3	70	60	30
4	100	60	30
5	70	40	90
6	100	40	90
7	70	60	90
8	100	60	90

The order of the tests were then randomly selected to insure that all bias effects were removed. The test series obtained using this technique is as follows:

Run No.	Temp.	Current	Time
1	70	60	90
2	100	60	30
3	70	40	30
4	100	40	90
5	100	40	30
6	70	40	90
7	70	60	30
8	100	60	90

A statistical analysis of the results obtained from these tests enable determination of both primary effects (temperature, current, time) and interaction effects (time and temperature, current and temperature, etc.). The analysis is based on calculating the effective resistance (R_{eff}) based on the measured input power and armature current.

The significant results from the statistical analysis are the following:

- The overall average or "best estimate" for the short circuit resistance is 3.53 microhms.
- We can say with 95% confidence that the effect of variations of current, temperature, and duration is at most ± .3 microhms.
- We can say with 95% confidence that all values of the mean R_{eff} between 3.33 and 3.71 microhms are not contradicted by the data.
- The data does not contradict the possibility that none of the variables has a significant effect upon the effective resistance - at least over the range of variation used in obtaining the date - and that all deviations are simply due to random error.

The air gap design was modified to increase the circumferential uniformity of the air gap flux. Iron bars were inserted in the top of the stator slots. This resulted in a magnetic circuit similar to semi-closed slots in conventional machines. An analysis of test data taken during the contact resistance tests above show a net reduction of parasitic losses from 10 KW to 6 KW.

Following the previous test, a pulse test was run. This test consists of energizing the excitation coils with a step function pulse while observing the growth of the load current (short-circuit load). The procedure was to first adjust the excitation power supply to establish a 50 KA short-circuit current in the blank end module, then turn off the supply, wait for the load current to decay to zero, and then throw the supply switch "ON". Oscilloscope traces of both excitation current and short circuit current are shown in Figure 2.1.3A, B, C, at sweep rates of .005, .5, and 1 second/div respectively.

We attribute the large turn-on transient in excitation current between 0 and 200 μ seconds to the coil capacitance. We can explain the lag between excitation and load current to magnetic diffusion within the solid iron rotor and stator. The diffusion time constant, τ, is approximately $= \mu\sigma d^2/\pi^2$

where μ = permeability

σ = conductivity

d = representative distance

using $\mu = \mu_r\mu_o = (150)(4\pi\ 10^{-7})$ Hy/M

$\sigma = 4 \times 10^6$ mho/M

$d \simeq 3'' = .075$ M

we get $\tau \simeq .5$ second, which is consistent with the observed waveforms. Also note that while the excitation current grows at an exponential rate $(1 - e^{-Kt})$, the slope of load current vs time is not indicative of a smooth exponential -- and this is what we expect with a variable permeability medium such as iron.

Figure 2.1.3B with a .5 sec/div sweep rate clearly shows the non-exponential slope of shunt current vs time. The ac component of the short-circuit shunt current produces the funnel shaped trace of Figure 2.1.3C.

This series of tests represents the completion of the experimental program for the SEGMAG with liquid metal current collectors. As a result of this program generalized conclusions can be drawn for homopolar machines using liquid metal current collectors.

- There exists a current collector critical temperature below which the collector will not function properly. This temperature increases with collector tip speed. This is particularly important in high speed machines where critical temperatures may be above 100°C. Additional work is required to develop a fundamental understanding of this phenomenon so that it may be minimized.

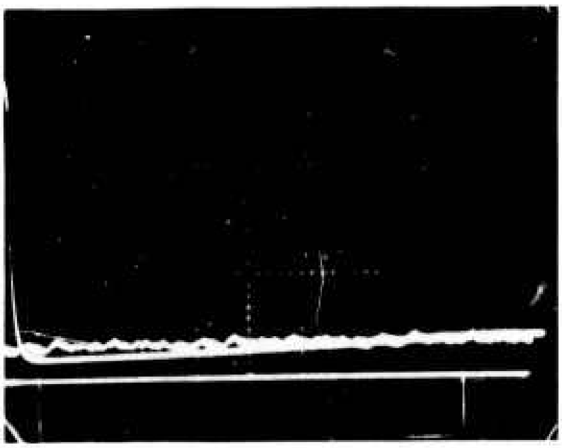


Fig. 2.1.3A
5. ms/Division Sweep Rate

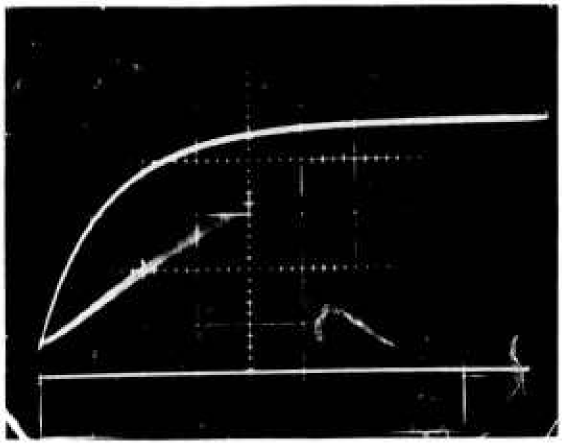


Fig. 2.1.3B
0.5 s/Division Sweep Rate

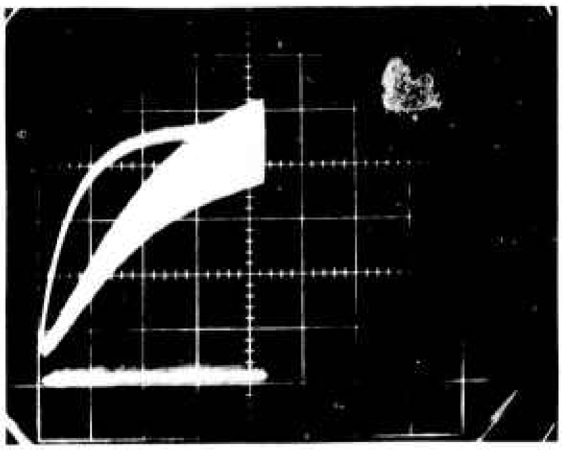


Fig. 2.1.3C
1.0 s/Division Sweep Rate

- The contact resistance between the NaK and metallic portions of the current collector may be significant. Although this tends to lower the eddy current loss due to radial leakage flux, it may introduce a significant loss in the collector due to armature current. The contact resistance therefore must be adjusted for minimum total loss. Additional work is required to determine the parameters that effect contact resistance so that this adjustment may be possible.

- The NaK used in the current collector must be purified for proper operation. Continuous purification was provided for SEGMAG and may be required for all liquid metal homopolars. Evidence of contamination was noted even though oxygen and water vapor levels were maintained below one part per million.

- The machine design must provide for leakage of NaK from the current collectors. Current collectors can be designed for very low leakage rates. However even minute leakage rates can accumulate to a significant amount over extended periods of operation. In addition, transients or accidents may introduce liquid metal into the machine internals. Internal shorts due to NaK accumulation can be disastrous.

- The expulsion forces due to the interaction of machine flux and armature current is a significant problem. These expulsion forces were encountered during the SEGMAG test program even though the leakage flux in the collector area was below 1 kG.

The successful testing of the SEGMAG generator demonstrates the feasibility of machines of this type. However, certain problem areas have been defined and must be carefully considered in future machine designs.

Due to the re-direction of the contractual scope to solid brush current collection, further pursuit of this liquid metal SEGMAG was terminated.

2.2 GEC GENERATOR

2.2.1 Objectives

The General Electric Company, Ltd., of England has developed an experimental homopolar generator which utilizes a GaIn current collection system. This generator employs an electrochemical purification system to maintain the purity of the liquid metal and avoid the "black powder" problems of previous investigators who used this metal. ARPA has approved purchase of this generator for experimental evaluation under the contract. The machine will be used to provide operating and technical experience with GaIn as a current collector liquid and to supplement the main experimental studies which will be conducted with NaK. This experience is expected to be valuable in broadening the scope of the program beyond the alkali metals. The physical design of the machine and its performance will be investigated thoroughly, and the unit may also be employed as a high current dc source in the current collector test program.

2.2.2 Prior and Related Work

Liquid metal current collection systems have a high potential to function efficiently with long, trouble free life in the face of high electrical current loads and high rotational speeds conceived for homopolar machines of the advanced segmented magnet design.

Based on extensive study, NaK-78 was selected as the best liquid metal for current collectors employed in the SEGMAG machine, and GaIn was selected as the alternate choice.

Since GaIn has been identified as the back-up choice to NaK, the ability to work with and study a functioning GaIn unit is expected to be highly instructional in the general sense and also to shorten any subsequent development effort with GaIn.

Based on an extensive search of the market we have concluded that the GEC machine is the best vehicle to provide the GaIn experience needed for this program. No other liquid metal machine in the world, to our knowledge has operated continuously longer than 40 hrs without maintenance. Therefore, this machine, which has operated up to 1000 hours with no problems, represents a unique development.

The GEC generator is a vertical shaft machine utilizing GaIn liquid metal eutectic as the slip ring contactor. The generator is rated at 16,000 amperes, 8 volts when driven at 3400-3600 rpm. Figure 2.2.1 displays schematically the GEC generator vertical shaft concept.

The GaIn purification cell was severely damaged in shipment. A replacement cell was fabricated by Westinghouse using detailed drawings furnished by GEC Company.

The GEC generator test stand was completed in Phase II, and the machine was installed. The test stand is powered by a 50 HP 1750 rpm AC machine, and a drive train provides speeds of 1800 and 3600 rpm.

Installation of the auxiliary equipment was completed, including cover gas, cooling water, and instrumentation. The GEC machine was then successfully tested to verify its performance and to study the GaIn current collector system.

The following are the four basic tests performed on the GEC machine:

1) An open circuit test, to determine no-load voltage and current collection magneto-hydrodynamic losses as a function of field current.

2) A machine short circuit test, to determine the I^2R losses in the machine.

3) A motor test, to measure the vibration levels, magnetohydrodynamic losses, and coastdown time.

4) An endurance test, to confirm the performance capability of the machine and its auxiliaries over a long time period. Liquid metal loss rate, cell performance, argon contamination and seal performance were monitored.

The test results obtained from this program have enabled the machine losses to be segregated into three categories:

- Machine friction and windage losses with GaIn in the collector.
- MHD losses due to leakage flux in the current collector.
- Joule heating losses due to current flow in the machine.

The viscous, friction and windage losses were determined at various speeds and zero excitation by measuring the input power to the coupled drive motor. The difference between this power and the uncoupled drive motor losses at each speed determined the generator losses. The friction and windage losses cannot be separated from the liquid metal viscous losses because gallium indium could not be completely excluded from the collector areas during the test to measure friction and windage losses.

During Phase II, the acceptance tests were successfully performed in England at The General Electric Company, Ltd., and witnessed by Westinghouse personnel. These tests consisted of open circuit, short circuit, generator load, motor and an endurance test. The proper operation and maintenance of the unit were also demonstrated.

Dwg. 6251A96

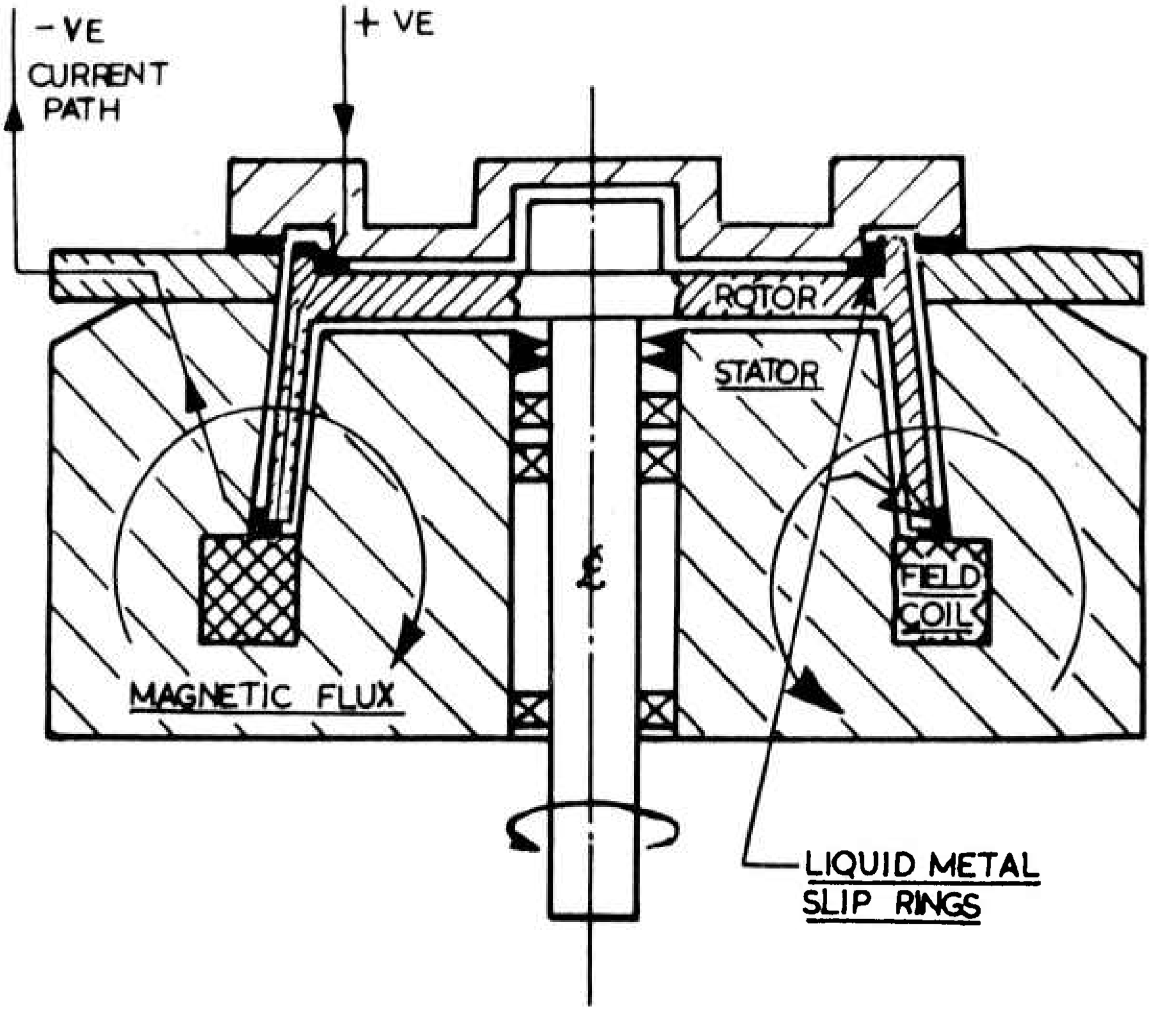


Fig. 2.2.1: GEC vertical shaft homopolar machine schematic

The MHD losses were determined during open circuit tests at various speeds and field currents. The power losses increased with speed due to viscous losses, and with excitation due to the interaction of leakage flux with currents induced in the liquid metal of the collector. These currents induced by the leakage flux resulted in losses that became significant at higher speeds and excitation levels.

The I^2R losses were determined by the short circuit tests. The sum of friction, windage and viscous losses were subtracted from the power losses measured during short circuit to determine joule heating losses in the machine. The MHD losses were neglected because of the low machine flux during short circuit.

The losses measured during the test program at 3600 rpm are:

Viscous, friction, windage	6.2 KW
MHD	1.0 KW
I^2R	7.0 KW
Total losses	14.2 KW

For the 100 KW GEC machine the overall calculated machine efficiency was 85.8%. At lower speeds the efficiency rises to a level approaching 94%.

The GaIn liquid metal was purified by an electrolytic regenerative cell during the entire test. The cell performed well during the entire program with no evidence of GaIn contamination.

2.2.3 Current Progress

Evaluation of the GEC machine was completed in a previous report period and is described in the fifth semi-annual technical report (E.M. 4648, February 1975).

This machine will be used as a high-current source for the solid brush test rigs of Phase III-A of this contract (Part C of this report).

2.3 SEGMENTED MAGNET HOMOPOLAR TORQUE CONVERTER (SMHTC)

2.3.1 Objectives

The objective of this program is to investigate the segmented magnet homopolar torque converter (SMHTC), within the framework of some of the more promising applications. This concept will then be demonstrated in a torque converter which will operate at constant input speed (as from a prime mover), and will provide variable output speeds, in both forward and reverse directions, at variable torque up to full power rating.

Our objective in Phase I was to study the various configurations proposed for the SMHTC, and the technical problems involved in developing the prototype machine.

In Phase III a conceptual design is to be evolved for the prototype torque converter.

2.3.2 Prior and Related Work

The SMHTC consists basically of two homopolar machines connected as a generator-motor set. Two basic configurations are being considered: (1) a radial design which uses a generator mounted within a motor; and (2) an axial design which consists of inline generator and motor. At present, the inline configuration is preferred.

Two basic homopolar machine types are being considered: (1) the drum-type (SEGMAG), and (2) the disk-type (DISKMAG).

During Phase I of this contract, electrical analyses of large (30,000 HP) and small (6000 HP) machines were completed.[1] These were of the drum-type (SEGMAG) homopolar machine configuration. Two conceptual designs (radial and axial) were also prepared for the 6000 HP machine, as part of the Phase I effort.

More recent studies (in Phase III) have shown that a rating of 8000 HP, 3600/500 RPM is typical of potential applications to small naval ship drives,[2] and this rating was therefore chosen for the prototype torque converter.

Previously in Phase III, a number of 8000 hp designs for the disk-type "flooded gap" machine (DISKMAG) were investigated.2 The power losses and internal machine fluid pressures associated with a particular "flooded gap" design were defined. The major areas of concern found for the 8000 HP "flooded gap" design are:

- Complex construction of disks to obtain magnetic circuits with low axial and high circumferential reluctance.
- High machine power losses, attributed mainly to MHD effects in the axial gaps between disks.
- Probability for turbulent rather than laminar flow and high short circuit losses in the liquid along the flat side walls of the machine disks. Reynolds to Hartman number ratios >1000 are calculated for operating conditions down to 30% of rated full load speed. Thus, the assumption of laminar fluid flow employed in the axial gap power loss expression is in doubt except at low speeds.
- A need is recognized for large thrust bearings and high pressure shaft seals to assure a fail safe machine design.

A conceptual design was prepared for the 8000 HP torque converter of the SEGMAG type.[3] This machine will accept input power from a gas turbine prime mover at 3600 rpm and deliver power to a propeller load at variable speeds to 500 rpm in either forward or reverse directions.

In addition, a conceptual study of a large (40,000 HP) DISKMAG propulsion motor was performed.[3] Electrical design and loss studies were performed to develop optimum configurations for maximum efficiency and power density.

However, the inherent low efficiency of this DISKMAG type of machine precludes its use in the applications of interest. Thus, the focus of the conceptual design study should in the future be concentrated on the SEGMAG (drum-type) torque converter configuration.

2.3.3 Current Progress

Investigation revealed that a satisfactory control system for the torque converter is achievable.

The basic torque converter system investigated was a combination of SEGMAG machines consisting of a single dc generator driving a single dc motor by armature voltage control. Generator field control was used to control armature voltage over the entire speed range.

For the case of one generator supplying several motors at slight differences in speed, motor field control was utilized. However, for most operational requirements the motor fields are held constant.

Using static excitation control for the generator field, the output voltage can be controlled very rapidly over the entire speed range due to the very short time constant of the generator field. Excitation control is coupled to the prime mover fuel control to enable the generator to operate near constant speed over most of the power range.

During reversals, dynamic braking is utilized to absorb the kinetic energy of the load. Since it is desirous to complete this maneuver quickly in order to reverse the motor by armature voltage it is necessary to switch the high armature currents. This appears to be the main problem in this system as high current dc switches are not as readily available for large drive systems as they are for smaller capacity systems.

Reverse operation speed control is similar to forward speed control through armature voltage control via the control of the generator field.

Specific application data would have to be made available for detailed control system analysis. However, there appear to be no insurmountable problems to the achievement of a satisfactory and practical control system for Segmented Magnet Homopolar Torque Converters (SMHTC).

2.4 REFERENCES

1. C. J. Mole, et. al., "Design and Development of a Segmented Magnet Homopolar Torque Converter," Semi-Annual Technical Report for May 31, 1973, June, 1973, E.M. 4518.

2. C. J. Mole, et. al., "Design and Development of a Segmented Magnet Homopolar Torque Converter," Semi-Annual Technical Report for Nov. 30, 1974, Feb. 1975, E.M. 4648.

3. C. J. Mole, et. al., "Design and Development of a Segmented Magnet Homopolar Torque Converter," Semi-Annual Technical Report for May 31, 1975, July 1975, E.M. 4705.

SECTION 3

APPLICATION STUDY

3.0 OBJECTIVES

Review and select promising applications for the segmented magnet homopolar machines and torque converters.

Several of the applications resulting from the Phase II application studies will be reviewed in conjunction with ARPA, and the most useful application will be selected.

3.1 Current Progress

Due to the redirection of the contractual scope from liquid metal to solid brush current collection, the application studies performed during this period are reported in Part C, Section 3 of this report.

SECTION 4

CURRENT COLLECTION SYSTEMS

4.0 OBJECTIVES

The objectives of this task are to study liquid metal current collection technology and to identify the preferred systems for the segmented magnet homopolar machines.

During Phase I the specific objectives were: 1) to review the state-of-the-art of liquid metal current collection system technology; 2) to identify preferred liquid metals and preferred current collector designs under a variety of operating conditions; 3) to identify the operational problem areas which must be resolved for successful performance; 4) to establish the constraints which the liquid metal handling and purification systems must satisfy; and, 5) to establish an experimental program to resolve the problems associated with liquid metal current collectors.

During Phase II the objective was to evolve a liquid metal current collector suitable for unidirectional, constant speed machines of the SEGMAG type and to verify its effectiveness in the 3000 HP demonstration SEGMAG generator.

During Phase III the current collector technology
1) unidirectional high speed (96 m/s collector speed) generator applications; and, 2) reversible and variable speed applications such as motors and torque converters.

4.1 Current Progress

Work on this task was terminated due to the re-direction of the contractual workscope from liquid metal to solid brush current collection.

SECTION 5

LIQUID METAL SUPPORT SYSTEMS

5.0 OBJECTIVES

The objectives of this Task are: 1) to investigate the compatibility of candidate machine materials with NaK and GaIn as well as with potential decontamination solutions; 2) to perform literature, analytical, and experimental studies to identify suitable materials and suggest alternate choices where necessary; 3) to design, fabricate, and test the liquid metal loop and cover gas systems that will be required in the SEGMAG generator; and 4) to establish the operating parameters and interactive responses of these systems.

During Phase I, the objectives were to identify the materials requirements and related problems for the segmented magnet homopolar machine, with particular emphasis to the long term compatibility problems between the selected liquid metal and the electrical conductors, insulation and structural materials in the system.

In Phase II, the objectives were: 1) to identify experimentally the SEGMAG machine materials that are compatible with NaK; 2) to provide a test facility to evaluate candidate current collectors under simulated machine environment; 3) to provide liquid metal and cover gas systems for the SEGMAG demonstration machine; and, 4) to provide test facilities for the SEGMAG and GEC machines.

During Phase III, the auxiliary equipment developed under Phase II was utilized in the SEGMAG test program. The SEGMAG liquid metal system was further developed and simplified. Support systems were considered for use in torque converter and motor applications where reversible and variable speeds are encountered. GaIn technology studies were pursued with respect to machine requirements.

5.1 CURRENT PROGRESS

Due to the re-direction of the contractual scope from liquid metal to solid brush current collection, further pursuit of this task was terminated.

SECTION 6

SEAL STUDY

6.0 OBJECTIVES

A study of the sealing problems between the liquid metal, bearing oil system, and the environment shall be conducted. Seal system designs will be evolved for both the SEGMAG and SMHTC machines.

There are two subtasks to the seal study:

1) Confinement of liquid metal to the current collection zone. This work is reported in Section 4, "Current Collection Systems".

2) Development of the seal systems for the primary rotor shafts of the homopolar machines. This work is reported in Section 6, "Seal Study".

During Phase I of this program, our objectives were, 1) to review the state-of-the-art of seal technology as applicable to homopolar machines, 2) design a test apparatus capable of evaluating the performance of various seal concepts under operating conditions anticipated in homopolar machine applications.

During Phase II our objective was to develop a shaft seal system for homopolar generator applications, where the mode of operation is both unidirectional and continuous. In particular, the goal was a shaft seal for the SEGMAG generator.

In Phase III, the seal technology is to be extended to, 1) torque converter and motor applications where reversible and variable speeds are encountered , and 2) unidirectional high speed (96 m/s collector speed) generators.

6.1 CURRENT PROGRESS

Due to the re-direction of the contractual scope from liquid **metal to solid brush current collection, further pursuit of this task was terminated.**

E.M. 4790

PART C

PHASE III-A SOLID BRUSH CURRENT COLLECTOR DEVELOPMENT FOR HIGH CURRENT DENSITY APPLICATIONS

PART C: SOLID BRUSH CURRENT COLLECTOR DEVELOPMENT FOR HIGH CURRENT DENSITY APPLICATIONS - PHASE III-A

SECTION 1

INTRODUCTION

1.0 BACKGROUND

Part C of this report describes the work performed under Phase III-A of this contract, which was initiated on July 1, 1975. The Phase III-A continuation will involve initiation of research and development of advanced current collection technology using a solid brush-gas-vapor-additive system. This development will have great potential value for reversing and other machine current collector systems.

The new current collection concept has already demonstrated extremely good performance using individual brushes in an humidified inert atmosphere, and represents an ideal reversing collector system for the torque converter and other machines. The technology may be extended to high speed generators and allow the development of a high voltage SEGMAG, thus reducing current transmission problems substantially and enhancing the utilization of SEGMAG by DOD.

1.1 OBJECTIVES

The principal objective of the Phase III-A program is to initiate the development of high power current collection systems for electrical machines, in order to increase the performance, life, and reliability of such machines. The individual steps are to (1) investigate the materials and atmospheres of current collection systems; (2) to select preferred technical approaches in terms of the materials system and requirements; (3) develop slipring and commutator current collection systems appropriate to reasonably large machines; and finally (4) to conduct extensive testing to determine the performance and life of such systems. The specific objectives of Phase III-A are summarized below:

1) Using suitable parameters for typical machines, evaluate promising materials and atmospheres, in terms of velocity, current density, pressure, life, losses, and voltage drop. Select suitable combinations for continued evaluation.

2) From the materials selected, construct large brushes and test in the preferred atmosphere.

3) Construct a slip ring system using a suitable array of solid brush materials and test for bulk properties at variable speed. Evaluate load current sharing problems.

4) Determine the brush loading and cooling system requirements for selected materials. Evolve a system concept and fabricate a model for initial tests.

5) Design and construct a model system using two sliprings to evaluate the solid brush SEGMAG concept, and to determine the potential future technical problems with such a system. Test over a wide range of speeds and loadings.

6) Conduct a continuous application study to correlate brush research with machine requirements and potential utilization. Assist in materials selection.

1.2 PRIOR AND RELATED WORK

Westinghouse has for many years been investigating the problems of power transfer across sliding electrical contacts (solid brushes). One of the results of this research was the demonstration that brush life can be increased 10 to 15 times by operating brushes in a humidified inert gas atmosphere rather than in air. These brushes are now in practical machine applications at current densities of 60 apsi.

Recent experimental work at Westinghouse has shown that very high current densities (3 MA/m^2, 2 $kA/in.^2$) can be achieved when solid brushes are operating in controlled inert gas atmospheres with water and/or other additives. Furthermore, substantially reduced friction coefficients and voltage drops across the interface have been achieved simultaneously, resulting in a predicted brush life in the range of 20,000 to 200,000 hours.

The improved operating performance of these and other new brush systems will improve the performance of existing commercial machines, and will improve the applicability and maintainability of advanced concept machines, such as SEGMAG. However, before these new solid brush systems can be fully utilized it is important to characterize and understand their performance, and this is the central feature of the investigations planned here.

SECTION 2

CURRENT PROGRESS

2.1 CURRENT COLLECTOR TEST RIGS

The development of solid brush SEGMAG machines required extensive experimental facilities to evaluate two principal areas:

- Brush Material Selection
- Current Collection System Evaluation

The brush material selection requires test rigs to evaluate individual brushes to determine coefficient of friction, double voltage drop, brush pressure and wear rate in specified environments. These test rigs are normally of reduced size and provide an initial screening of brush-slip ring material performance.

Evaluation of current collection system performance requires test rigs to study current sharing in multiple parallel connected brushes in flux leakage fields anticipated in machine applications. Concepts in brush restraint, brush shunts and brush cooling must be studied.

The test rigs required for these areas are summarized as follows:

B1 = Brush Tester #1

B2 = Brush Tester #2

HS1 = High Speed Brush Tester #1

HS2 = High Speed Brush Tester #2

MEB = Machine-Environment Brush Tester

B1 and B2 are duplicate testers for initial screening of protoypic materials in small (sub-size) brush configurations. During this report period B1 was operational.

HS1 and HS2 are duplicate testers for advanced screening of prototypic full-size materials under higher speed and higher current conditions than B1 and B2. During this report period HS1 was operational.

MEB will expose the brush and slipring materials and systems to an actual machine environment including high currents, multi-brush systems, and ambient magnetic fields. MEB is a model solid brush SEGMAG system.

2.1.1 Laboratory Brush Testers

2.1.1.1 Objectives

The objectives of the laboratory test rigs are to screen potential brush and slipring material combinations for performance over the desired current and speed range in a controlled environment. The parameters of particular importance are brush friction, current density, double voltage drop, and wear rate. The test rigs provide accurate experimental data on individual sub-size brushes in a controlled environment.

2.1.1.2 Prior and Related Work

No brush testers were previously available to satisfy the precise needs of the current program. However, because of Westinghouse's long involvement in the development of electrical sliding contacts, certain facilities were available for adaptation to this program.

2.1.1.3 Current Progress

Detailed descriptions of two laboratory "bell jar" slipring type testers are presented. One tester (B1) is for evaluating sub-size brushes and the other (HS1) is for full-size brushes.

(A) <u>Brush Tester #1 (B1) - FOR TESTING SUB-SIZE BRUSHES</u>

Brush Tester #1 (B1) is an existing Westinghouse facility that was adapted to the needs of this contract.

Figure 2.1.1 shows an idealized section of the B1 test chamber in which sub-size brushes are tested. The slipring is turned from a silver-copper alloy bar and, although the figure does not show this detail, its curved surface is helically grooved with a pitch of 1/4 inch and a width of 1/32 inch. The ring is 3.25 inches in diameter and is fitted with a tapered hole and bolted onto the end of an overhung shaft which enters through a small clearance hole in the steel plate that makes up one wall of the chamber. The 0.5 hp dc drive motor, not shown, drives the ring at infinitely controlled speeds to 6000 rev/min (5000 ft/min). Corresponding measurements of electrical power input to the drive motor and selected brake mechanical loads applied to the slipring surface provide calibration data for subsequent brush friction determinations.

The brushes are fashioned to close dimensional tolerances out of selected materials. The shunts are attached very simply. Gold-plated screws, to which the shunt wires have been soldered, are screwed firmly into holes which have been tapped in the brush. Such a contact to a

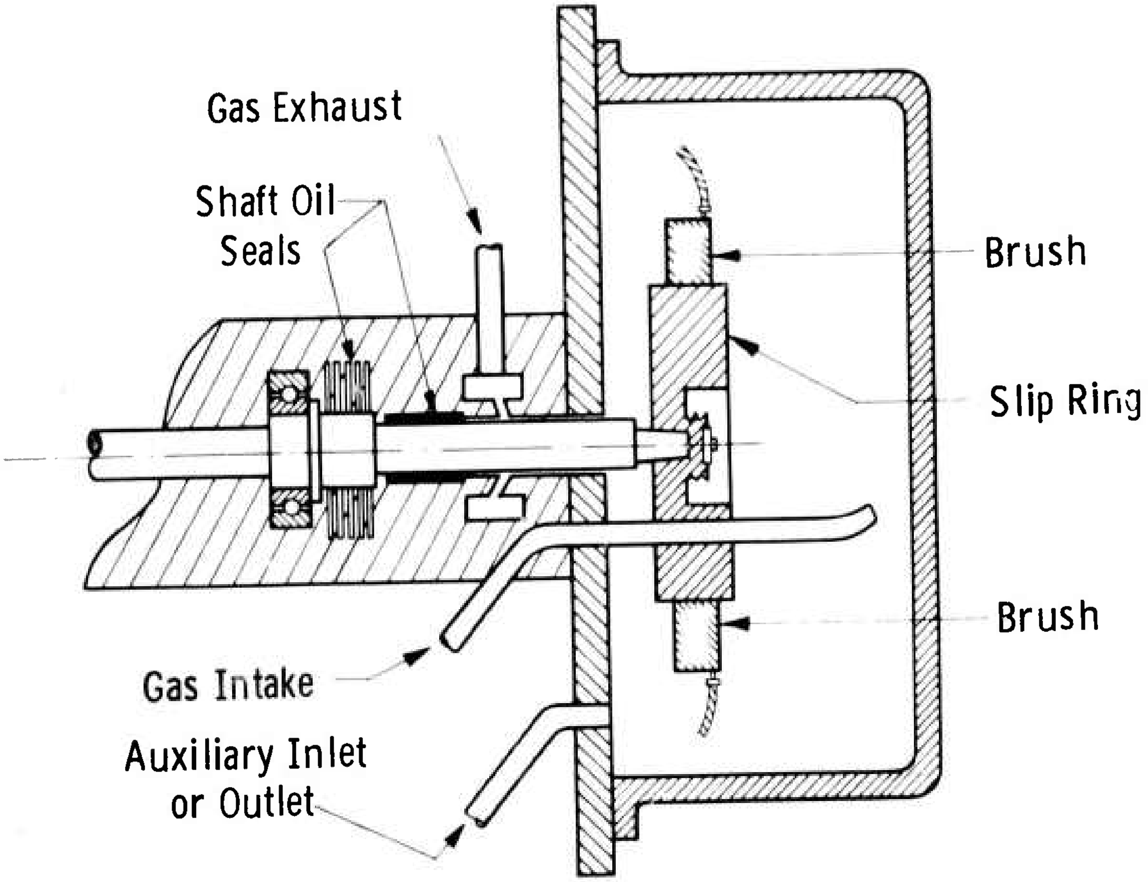


Fig. 2.1.1 Test Chamber of Type B1 Brush Tester

brush will pass high currents indefinitely and is equivalent in every way to commercial shunting devices, excepting the ability to resist vibration. The normal trailing-type brushholders were modified slightly to accept a larger number of shunts per brush. Each of two brushholders, located 180° apart, supports brushes 5/16 inch thick x 1/2 inch wide. The brushes, one positive and one negative polarity, are constrained to slide in a common track on the ring. Load current is transferred from the positive polarity brush into the slip ring, and then out again through the negative polarity brush. With this arrangement current flows in both directions through the slipring film, since both brushes ride in a common track. Cutting back portions of the brush face permits higher current density loading. Brush mechanical load is applied by clock type springs, using screw-locked adjustable pivot pins and calibrated weights.

Except on one side, the chamber is made up of a flanged glass vessel which is clamped to the steel side plate. The resulting inside ambient gas volume is about 0.07 cubic foot. The purified gas enters through one copper tube and leaves through a second which is let into the side of the cylinder which surrounds the rotating shaft on which the ring is mounted. The gas leaves the chamber at a pressure slightly above atmospheric and any traces of gases, which may get by the elaborate shaft seal and try to enter the chamber, are sucked out through the gas-exit tube along with the very much larger volume of gas which is deliberately passed through the chamber. Gas flow into and out of the test enclosure is at a rate of 2 ft^3/h, subjecting the brushes and ring to about one gas change every two minutes.

Prior to entering the test chamber, the gas is saturated with water by flowing through a bubble tower held at either 0° or 20°C. In the first case, the water content will be 2.1 grains per cubic foot (6000 ppm_v) and in the later 7.5 grains (23,000 ppm_v). The end of the entering gas tube of the bubbler is closed by a fritted glass filter which breaks the gas into extremely fine bubbles and this increases the speed with which it is wetted to the desired extent. From time to time the dew point of gas samples taken from the chamber is checked to make certain that the humidity is at the desired level.

The gas is finally exhausted to the laboratory ventilatio system.

Figure 2.1.2 shows an overall view of the test rig and associated apparatus. A water bubbler packed in ice is centrally located on the bench and a constant current supply, infinitely variable to 80A, and recording meters are located on the shelf above the tester. Electrical equipment for controlling the drive motor and measuring its power input is located on the bench to the right of the tester. Copper cooling-water feed and drain lines to and from the face plate and an air cooling fan are located near the test chamber.

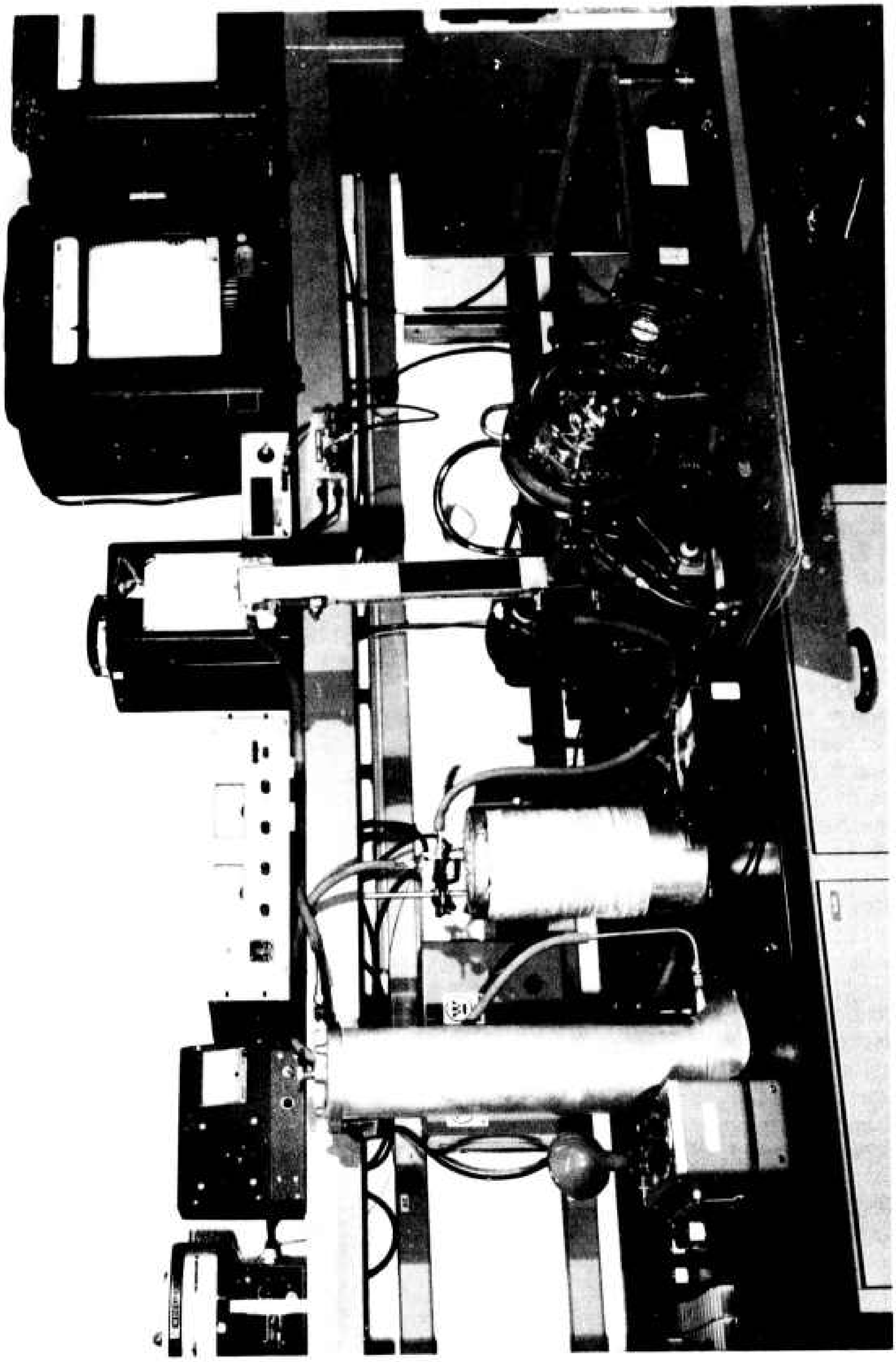


Fig. 2.1.2 Type B1 Brush Test System

(B) High Speed Brush Tester #1 (HS1) - FOR TESTING FULL-SIZE BRUSHES

Figure 2.1.3 shows the physical arrangement of components comprising the full-size brush tester used to obtain brush performance data under controlled gas atmosphere and high current test conditions.

The slipring is driven by a long slender shaft which extends about six inches above the drive motor housing. The copper or zirconium-copper alloy ring is six inches in diameter and the surface on which brushes slide is helically grooved, as previously described. Ring speeds up to 6500 rev/min (10,000 ft/min) may be obtained by varying the frequency of the electrical power supplied to the three phase 0.75 hp drive motor. The drive motor is calibrated by the prony brake method for brush test friction drag determinations, as previously described for the sub-size brush tester (B1).

Four brushes, two of each polarity, comprise a test set and they are held in a radial mode against the slipring. Each flat-top brush is 5/16 inch x 5/8 inch in cross-section with the longer side aligned in the circumferential direction. The brushes were confined by their holders to ride in two separate tracks according to polarity.

Load current is transferred from two parallel positive-polarity bruhes into the slipring along a common track, and then out again through two similarly connected but negative brushes along a common track that differs from the first. With this arrangement current flows in one direction through the slipring film, inward under the positive and outward under the negative brushes. Current distribution is ascertained from direct recording of millivolt drops developed across shunts connected in series with the individual brushes. Brush mechanical load is applied by flat-coiled constant-force springs.

The oil-lubricated guide and thrust bearings of the vertically mounted drive motor are located in the lower housing away from the test chamber. The air-tight motor frame is water cooled. Brush electrical load current is brought into the chamber through copper tubes sealed to the face plate by insulated bushings. These tubes also serve to transmit water for forced cooling of the radial type brushholders. Pairs of glass insulated compensated bushings "T" serve to carry thermocouple signals outside the tester for measuring brush, brushholder, ring, and ambient temperatures. Other insulated leads extend potential points to meters for measuring brush-ring contact voltages.

Test atmosphere gas, conditioned to a specific humidity level, is forced from a pressurized storage cylinder into the test chamber through a copper tube soldered to the tester face plate. After flowing in a turbulent manner around the slipring and brushes, the test gas must pass along the drive shaft for a distance of about four inches, then through the motor housing before exhausting to the room exhaust system. Any extraneous gases or vapors which may diffuse to the upper portion of the stand pipe

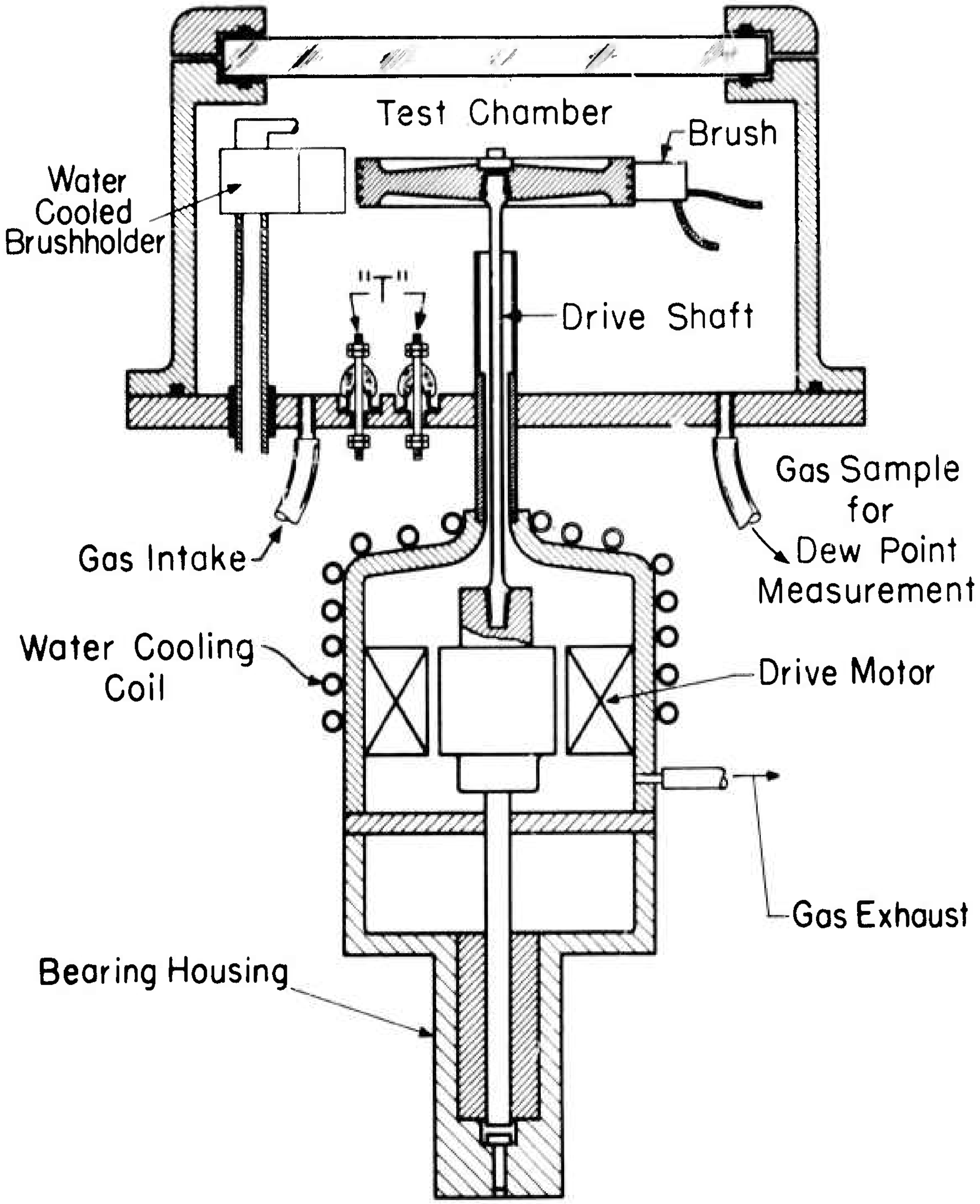


Fig. 2.1.3 Physical Arrangement of Components of Type HS1 and HS2 High Speed Brush Testers.

surrounding the drive shaft are drawn out through the exhaust tube, along with the large volume of test gas deliberately passed through the chamber. A second copper tube is located in the face plate through which samples of test atmosphere may be drawn for humidity and/or composition analysis.

Figure 2.1.4 shows two high-speed brush testers, (HS1 and HS2) one with the chamber bell removed. Immediately behind the testers is the drive motor electrical supply control panel. Not shown are the motor-generator sets which produce the variable frequency power for the tester drive motor. Also, not shown, is a rectifier which supplies smoothly controlled brush load current up to 1000A.

2.1.2 Machine-Environment Brush Tester (MEB)

2.1.2.1 Objectives

The objectives of this task are:

- To develop a test model (MEB) to evaluate solid brush current collection systems for high current density, low losses, and long operation life. The MEB will incorporate a single module segmented magnet homopolar machine concept with capabilities of 6 volts and 20,000 amps.

The Machine-Environment Brush Tester (MEB) will subject the current collectors to current densities, leakage flux and other conditions associated with operation in a machine environment. In addition, the unit will provide for long-term testing of current collectors, their attendant support systems, and the machine itself to develop operational data for solid brush machines.

2.1.2.2 Prior and Related Work

The previous ARPA supported effort leading to the successful development of the water-cooled, liquid metal Segmented Magnet Homopolar Generator (SEGMAG) has proven the basic concept of this machine design. The use of solid brush systems results in a reliable reversing collector for motor applications. This concept removes the complications associated with liquid metal current collectors and simplifies the overall system.

The result of various studies indicates that the minimum current density for a solid brush homopolar with equal volume to a liquid metal collector homopolar is 1000 A/in^2 (apsi). Since the initial solid brush-gas-vapor testing indicates solid brush current densities up to 2000 apsi, the solid brush SEGMAG machine will have a volume that is equal to or less than the equivalent liquid metal SEGMAG.

2.1.2.3 Current Progress

The Machine-Environment Brush Tester (MEB) consists of a single module SEGMAG configuration incorporating solid brushes in the current collection

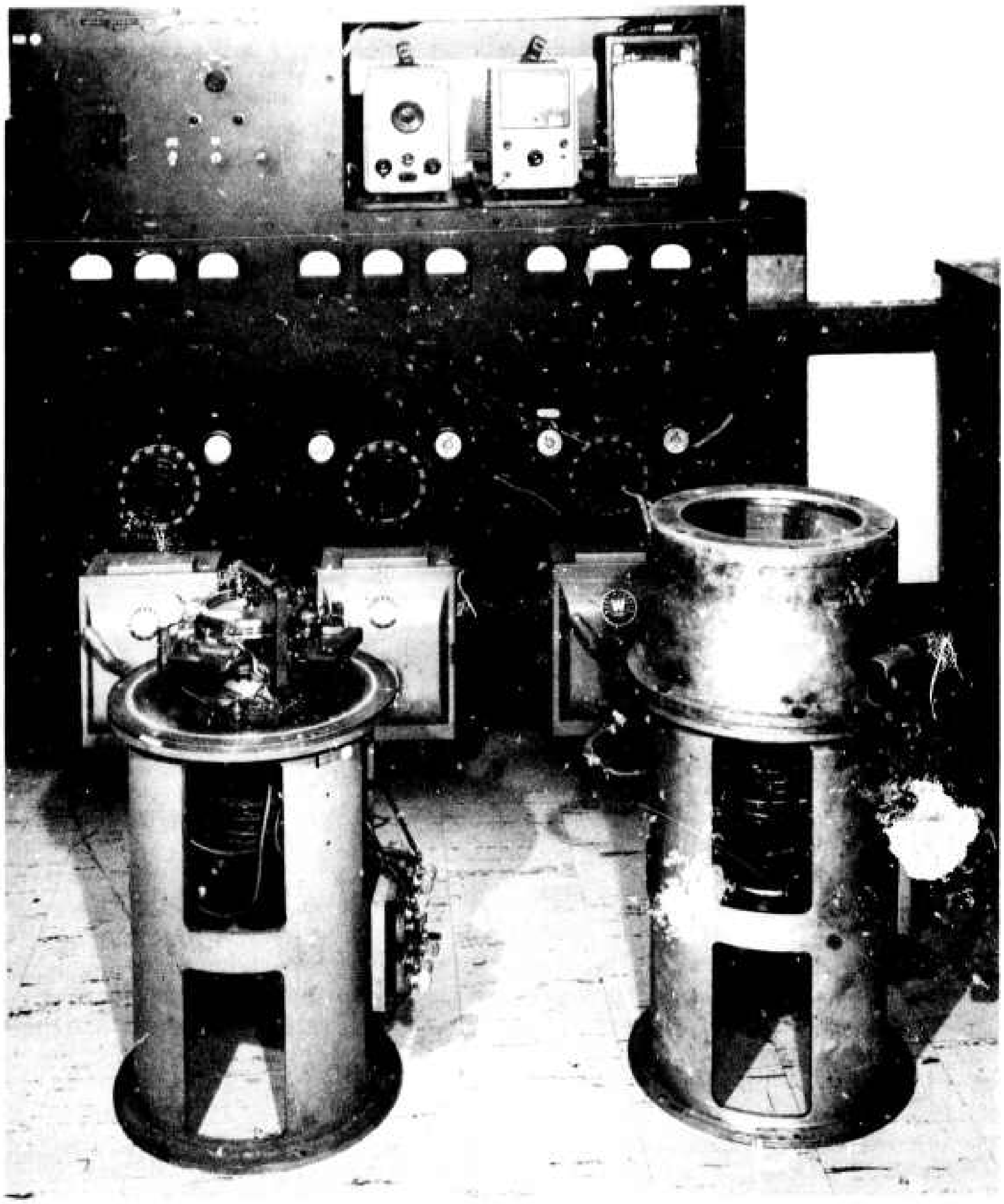


Fig. 2.1.4 High Speed Brush Testers (HS1 and HS2)

areas as shown in Fig. 2.1.5. The primary objective of MEB is to provide a test vehicle for the evaluation of solid brush current collection systems in a machine environment.

The mechanical design of the MEB must consider the same factors as those for the design of conventional rotating electrical machinery. In addition to the current collection system, the design of the MEB should incorporate simplicity and maximum flexibility of its components to minimize the down time between test sequences.

The following factors should be considered:

1) Mechanical conductor support

2) Rotor to stator alignment

3) Removal of losses

4) Machine environment

5) Erosion of cooling system components

6) Electrical insulation

7) Instrumentation

The rotor conductor drum must be restrained to withstand both centrifugal forces due to rotation and torsional forces due to the machine torque reaction. The torsional forces (8,000 in/lb) will be restrained by shrinking the copper conductor drum onto the iron rotor in the MEB. Since the rotor conductor drum and rotor iron have the same electrical potential, no insulation is required.

The support of the stator conductor is somewhat simpler since there are no rotational forces. The conductor drum will be restrained by an interference fit between it and the ferromagnetic stator iron. This concept provides adequate support to meet the 3/unit torque design criterion. Each stator conductor is insulated from the iron as well as from each other.

The alignment of the rotor in the stator is accomplished by four (4) positioning blocks, two (2) at each end of the test stand. These blocks provide vertical and horizontal adjustment capability. To measure the alignment, four (4) viewing ports are provided at each end of the machine at 3, 6, 9 and 12 o'clock positions. Measurements can be made of the rotor to stator gap at these locations and the proper adjustment can be made with the blocks. This arrangement provides maximum positioning flexibility for the systems including the possibility of testing brush operation with the rotor deliberately misaligned.

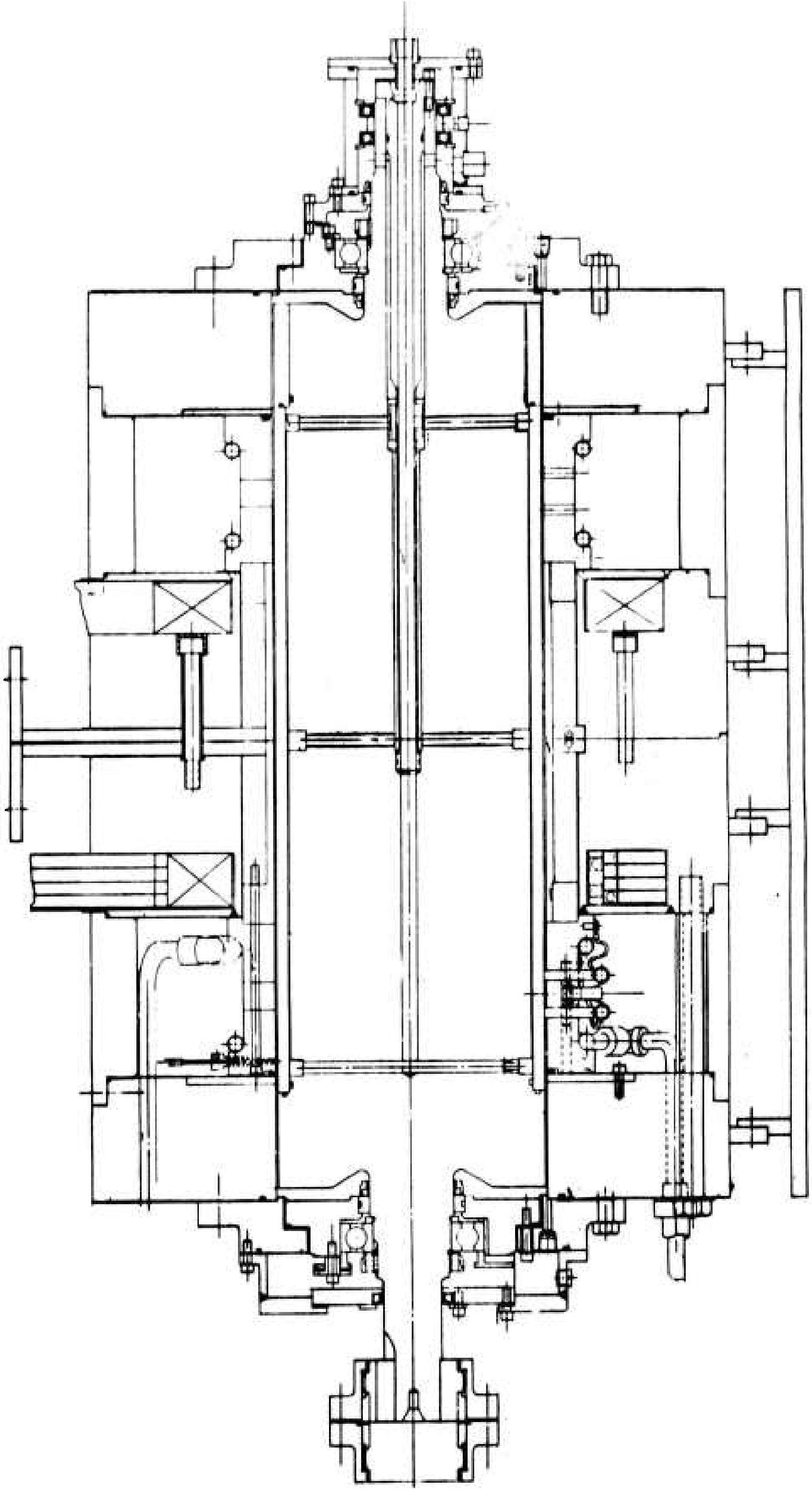


Fig. 2.1.5 Machine-Environment Brush Tester (MEB)

This test capability is very important since the run out of the slipring surface can adversely effect brush performance. Such run outs result in radial acceleration of the brush known as "brush bounce". This condition must be accommodated in the brush actuation gear to ensure proper contact pressure on the slipring for optimum life with minimum losses.

Rotor alignment is a function of the stator alignment provided by the rotor support structure, and dynamic deflection during operation. The MEB incorporates rolling element bearings which are adequate for the design loads and speed. Since the total flux of the machine must be carried by the ferromagnetic iron in the rotor, there is a substantial structural member in the active length and flux return path, thus resulting in a high critical speed for the machine. Because of high rotor stiffness, the dynamic deflection of the rotor will be small.

Water cooling has been used extensively in large turbine generators to remove machine losses. A similar system has been adopted for the MEB to provide cooling in the brush bearing area, machine leads and the rotor conductor drum.

The major losses requiring removal from the MEB include:

- Armature joule heating
- Brush friction
- Brush joule heating
- Friction and windage losses

The cooling system is designed to remove 80% of the machine losses through the rotor and 20% through the stator. The losses generated in the brush account for the majority of the total machine losses, and it must be removed through a sliding surface.

In the rotor the coolant is passed immediately below the rotor conductor drum in small channels (.38"W x .03"D) and provides parallel cooling path for the two collector areas. In this way the slipring temperature can be regulated to give optimal brush performance.

To control the environment within the MEB,shaft seals will be used. The shaft seals must be mounted inboard to the bearings to prevent contamination from the bearing lubricants. Since the environment will be adjusted for low brush friction, it is anticipated that conventional rubbing face seals will perform adequately.

The design provides for measurement of the important parameters. Temperature measurements of the rotor conductor, ferromagnetic iron as well as the slipring surface will be accomplished by thermocouples placed inside the rotor and brought out through sliprings. Brush temperature and potential drops from brush to brush will be measured by instruments imbedded in specified brushes. The machine torque will be measured by a torque meter installed between the MEB and the prime mover. Associated instrumentation of the stator, gas system, and the cooling water system will also be provided.

At present, the MEB is 60% complete.

2.2 CURRENT COLLECTOR CONTACT MATERIAL/PERFORMANCE

2.2.1 Objectives

The objective of this task area is to develop electrical sliding contact materials for high and medium-high current density applications. The goal requires low power loss at the contact interface and long life.

2.2.2 Prior and Related Work

Early experimental studies at Westinghouse showed that a marked increase in lifetime could be achieved when carbon and metal-graphite solid brushes were operated in inert gas atmospheres rather than in air.[1] The original work along these lines was undertaken prior to World War II and has continued to date.[2] Until recently, conventional current densities have been employed. Commercial verification is provided by the use of conventional brushes in synchronous condensers, where brush lifetimes of more than 100,000 h/in (>10 y/in) have been achieved.

No attempt was made until recently to extend the current density capability beyond the conventional level, (60 A/in^2), since no requirement for such brushes existed. However, within the last year this situation has changed. Brush tests were conducted in 1974, with the objective of achieving current densities of 300 to 500 A/in^2 and a long life. These tests, which were run at a relatively low speed of 2500 ft/min typical of motor applications, were extremely successful.

The low voltage drop and friction factor and long brush life observed during these tests were unexpected and led to a decision to conduct tests at even higher current densities, to permit the possibility of utilization in SEGMAG machines to be assessed. These tests were conducted at up to the current collector test stand limit of 2000 A/in^2 (i.e., more than 30 times the conventional brush current density), again with excellent results.

These encouraging results forced a reassessment of the role of solid brushes for homopolar dc machines, since even independent analyses[3] have shown that solid brushes become attractive for these machines at current densities >1000 A/in^2.

2.2.3 Current Progress

Most of the work during this period was devoted to modifying existing brush test rigs and developing the Machine-Environment Brush Tester (MEB). Brush material screening tests with the former rigs have commenced.

Eight brush materials were tested under electrical current density loads ranging from 300 to 2500 A/in^2. These screening tests are preliminary to the goal of developing an electrical sliding contact system which will operate with long life and with low power loss in advanced design electrical machines.

Before discussing the brush material experiments, a description will be given of the test procedure. All tests were made with the previously described (Sec. 2.1.1) laboratory "bell jar" slipring type brush testers.

2.2.3.1 Testing Procedure or Factors

The material test work completed during this period was exploratory in nature. In the main, screening type tests were conducted with selected available brush stock materials, to evaluate their feasibility for high (2000 A/in^2) and medium-high (500 A/in^2) current density applications. Copper and silver-graphite materials are considered prime candidates for the high current density and electrographite and metal graphite materials for medium-high density usage.

Prior to each run the slipring surface was cleaned by abraiding with 240 grit alundum cloth. This technique permits repeated generation of fresh metal surfaces with roughness values in the range 15-18 micro-inches. Total indicated run-out of the sliprings is less than 0.0005 in.

Prior to starting each run the brush faces were run-in to achieve good conformity with the slipring surface curvature. Linear brush wear was determined from pre- and post-test brush length measurements made with a special micrometer-jig fixture.

Nominally, each test run was 24 h in duration, unless terminated earlier due to unusual circumstances such as accelerated brush wear. Where life was very long, a few 70-h tests were run in order to obtain a more accurate determination of brush wear rate. Although the brush mechanical load force was an independent variable, a minimum value was required to achieve arcless current transfer. The threshold value varied for each material, but depended mainly and directly upon the electrical load level. Experiments were started after thoroughly purging air from the chamber enclosure with the conditioned test gas.

The brush-ring interface temperature is recognized as an important test condition. Low temperature is necessary to achievement of the high current density brush performance goals. Limited control of the interface temperature was achieved by gas convection cooling in both laboratory testers, with additional conduction cooling provided by circulating chilled water through the brushholders in the full-size brush tester. The MEB tester, described previously, is being fabricated and will incorporate forced water cooling of the sliprings as well as the brush-holders. Other test capabilities of this tester include ambient magnetic field, large numbers (50) of parallel-connected brushes, and load currents and ring speeds to 20,000 A and 14,000 ft/min, respectively.

Regarding results of work reported on here, the following brush-ring test conditions or factors are considered independent variables: mechanical load, electrical load, ring speed, environment gas, brush size, brush shape, and brush physical support. These variables were set prior to each run.

Measurements of the dependent response variables permit either direct or indirect determination of contact voltage drop, friction coefficient, brush face power loss density, brush life, and current distribution. Average results of the above determinations provide the data for comparison of brush materials.

Brush face power loss, W_B, is composed of mechanical and electrical components. In the absence of magnetic fields, terms of the following expression represent the mechanical and electrical power loss density components, respectively.

$$W_B = 0.0226\ \mu p v + J V_{SCD},\ \text{W/in}^2 \qquad (2.2.1)$$

where: μ = brush-ring friction coefficient

p = brush apparent mechanical load, lb_f/in^2

v = slipring speed, ft/min

J = brush current density, A/in^2

V_{SCD} = single brush contact drop, V

Brush life, L, may be defined as the distance traversed along the slipring per unit to time divided by the volume of brush worn away during the same time period.

$$L = \frac{60\ v}{tw(\Delta \ell)},\ \text{ft/in}^3 \qquad (2.2.2)$$

where: v = slipring speed, ft/min

t = brush thickness, in.

w = brush width, in.

$\Delta \ell$ = change in brush length, in/h

2.2.3.2 High Current Density (500-2500 A/in^2) Brush Material Test Results

Initial exploratory high current density brush material test results are presented here. Two silver graphite materials (SG212, SG216), and three copper graphite materials (W933, CMO, CM1S) are included. All materials were tested in an inert gas atmosphere.

Experiments with B1 Brush Tester

Performance comparisons of silver graphite material grades SG212 and SG216 (1), operating at 2000 A/in^2 brush current density, may be made from the data in Table 2.2.1. Brushes of grade SG216 (1) were fabricated from a small lot of material and they allegedly contain a higher percent silver than grade SG212.

Although both positive and negative polarity brushes are involved here, an average brush-ring interface voltage drop is given. Additionally, these reported values exclude the brush body and flexible shunt lead voltage drops. Nonconventional shunts are being designed wherein the goal is to achieve a combined brush body and shunt voltage drop less than 0.02 volt.

Based on the test results, data in Table 2.2.1 reveal that grade SG216(1) brushes perform with lower contact voltage than SG212. This result (lower contact resistance) is consistent with higher silver content in the former material. Grade SG216 (1) brushes, however, function with higher friction coefficients than grade SG212. This, too, is consistent with the material compositions. Higher graphite content in the latter material will provide a greater potential for formation and maintenance of lubricating films at the brush-ring interface, resulting in lower friction. The importance of mechanical pressure to both silver-graphite grades is evident by the reductions in contact drop in the 15-20 lb$_f$/in^2 range. Despite ensuing higher mechanical friction losses when the pressure is increased to 20 lb$_f$/in^2, the net power loss (mechanical plus electrical) is reduced. With 25 lb$_f$/in^2 pressure, however, the contact drop and friction coefficient of grade SG212 increased. Thus, an optimum load pressure is required to achieve minimum power loss conditions. Considering all runs, a direct correlation tends to exist between the power loss density and total brushholder temperature. Grade SG216 (1) is quite good. In contrast, brush life of grade SG212 brushes is relatively poor. Thus, differences in metal content and/or processing of silver graphite brush materials are important in achieving low power loss and long life.

Table 2.2.1

Silver-Graphite Material Brush Test Results

(2000 A/in^2)

Ring Speed 2500 ft/min

Brush Material	Mech. Pressure lb$_f$/in^2	Single Brush Drop, V	Friction Coef., μ	Density, W/in^2	Brush-Holder Temp., ^{o}C
SG216(1)	15	.25	.15	627	101
SG216(1)	20	.055	.16	291	68
SG212	15	.38	.11	853	109
SG212	20	.33	.10	773	111
SG212	25	.38	.12	930	113

A more complete characterization of SG216 (1) grade brushes throughout a wide current density range is presented in Table 2.2.2.

Table 2.2.2

Performance Characteristics of SG216(1) Material Brushes

Ring Speed 2500 ft/min

Test Duration to 60 h

Brush Face Reduced to	Current Density, A/in^2	Mech. Pressure, lb$_f$/in^2	Single Brush Drop, V	Friction Coef., μ	Power Loss Density, W/in^2	Brush-Holder Temp., °C
Full	500	5	.12	.21	119	72
Full	500	7.5	.03	.24	117	73
Full	500	7.5	.02	.24	112	71
Full	500	10	∿0	.23	130	71
Full	500	10	∿0	.28	158	81
Full	500	12	0	.26	176	81
Full	500	15	0	.22	186	87
Half	1000	5	.33	.15	372	103
Half	1000	10	.14	.21	259	77
Half	1000	15	.015	.22	201	67
Third	1500	15	.055	.17	227	67
Fourth	2000	15	.25	.15	627	100
Fourth	2000	20	.055	.16	291	68

Experiments with HS1 High-Speed Brush Tester

Performance comparisons of silver graphite grade SG216 (2) and copper graphite grades W933, CMO, and CM1S may be made from recorded date in Table 2.2.3. Grade SG216 (2) material was reported by the supplier to contain the same percent silver as grade SG216 (1), but it was processed somewhat differently. Metal content of the copper-graphite materials is claimed to higher than that of the silver-graphite material.

Table 2.2.3

Performance Characteristics of Selected Metal-Graphite Material Brushes

Ring Speed 5000 ft/min

Brush Grade	Current Density, A/in^2	Mech. Pressure, lb$_f$/in^2	Single Brush Drop, V	Friction Coef., μ	Power Loss Density, W/in^2	Brush Temp., ^{o}C
SG216(2)	500	11.0	.07	.16	233	57
"	500	15.2	.06	.18	338	69
"	500	22.7	.03	.17	451	77
"	1000	15.2	.16	.14	400	89
"	1000	22.7	.09	.15	470	83
"	1500	15.2	.21	.10	486	105
"	1500	22.7	.14	.10	467	97
"	2000	15.2	.19	.09	524	109
"	2000	18.5	.15	.09	478	107
"	2000	22.7	.12	.09	471	104
"	2000	22.7	.13	.09	491	102
"	2500	22.7	.14	.09	581	114
W933	500	11.0	.035	.22	290	68
"	500	15.2	.025	.32	561	105
"	1000	11.0	.065	.20	313	70
"	1000	15.2	.045	.31	576	108
"	1500	15.2	.065	.29	594	112
"	2000	15.2	.060	.28	600	120
CM1S	500	7.6	.10	.21	227	67
"	500	11.0	.11	.15	241	70
CMO	500	11.0	.13	.24	360	83

Figures 2.2.1 and 2.2.2 illustrate the contrasts in contact voltage and friction coefficient between the material grades. Copper graphite grade W933 performs with very low contact voltage, but with higher friction drag. Much higher mechanical load pressure is required of silver graphite grade SG216 (2) brushes to achieve equally low contact voltage, but with significantly lower friction coefficients. Copper-graphite grades CMO and CM1S brushes appear to function with higher contact voltages and friction coefficients, than silver-graphite grade SG216 (2).

Brush life was relatively low for the copper graphite grades listed in Table 2.2.3. This is not too surprising, since they possess very high metal content and, thus, lack lubricating capability.

2.2.3.3 Medium-High Current Density (to 500 A/in^2) Brush Material Test Results

Results of exploratory brush material tests involving medium-high current densities are presented here. Three silver graphite materials (SG212, SG216 (1), SG216 (2)), one copper graphite material (CM3B), and two electrographitic materials (W417, W457) are included.

Experiments with B1 Brush Tester

Performance comparisons of silver graphite grades SG212, SG216 (1), and SG216 (2), copper graphite grade CM3B, and electrographitic grades W417 and W457 may be made from the data in Table 2.2.4. Certain data from Table 2.2.2 are represented here for convenience. Although the metal content of all silver and copper-graphite materials is comparable, the SG216 grades possess somewhat higher amounts. The electrographite materials, of course, contain no additions of metal in their structure.

Perhaps the most notable information in Table 2.2.4 is the extraordinary long life associated with the electrographitic brush grades, especially grade W417. This characteristic is attributed to maximum availability of graphite at the sliding contact interface.

It seems very likely that the overall performance of electrographitic brushes will be improved with an increase in load pressure. Here, a reduction in brush life is an acceptable compromise in light of an anticipated decrease in the total power loss.

Based on these preliminary tests, electrographitic materials appear to be prime candidates for use as brushes in medium-high current density applications. This must be verified in machine environment tests, involving large numbers of brushes, typical load currents, and ambient magnetic fields.

Curve 683617-A

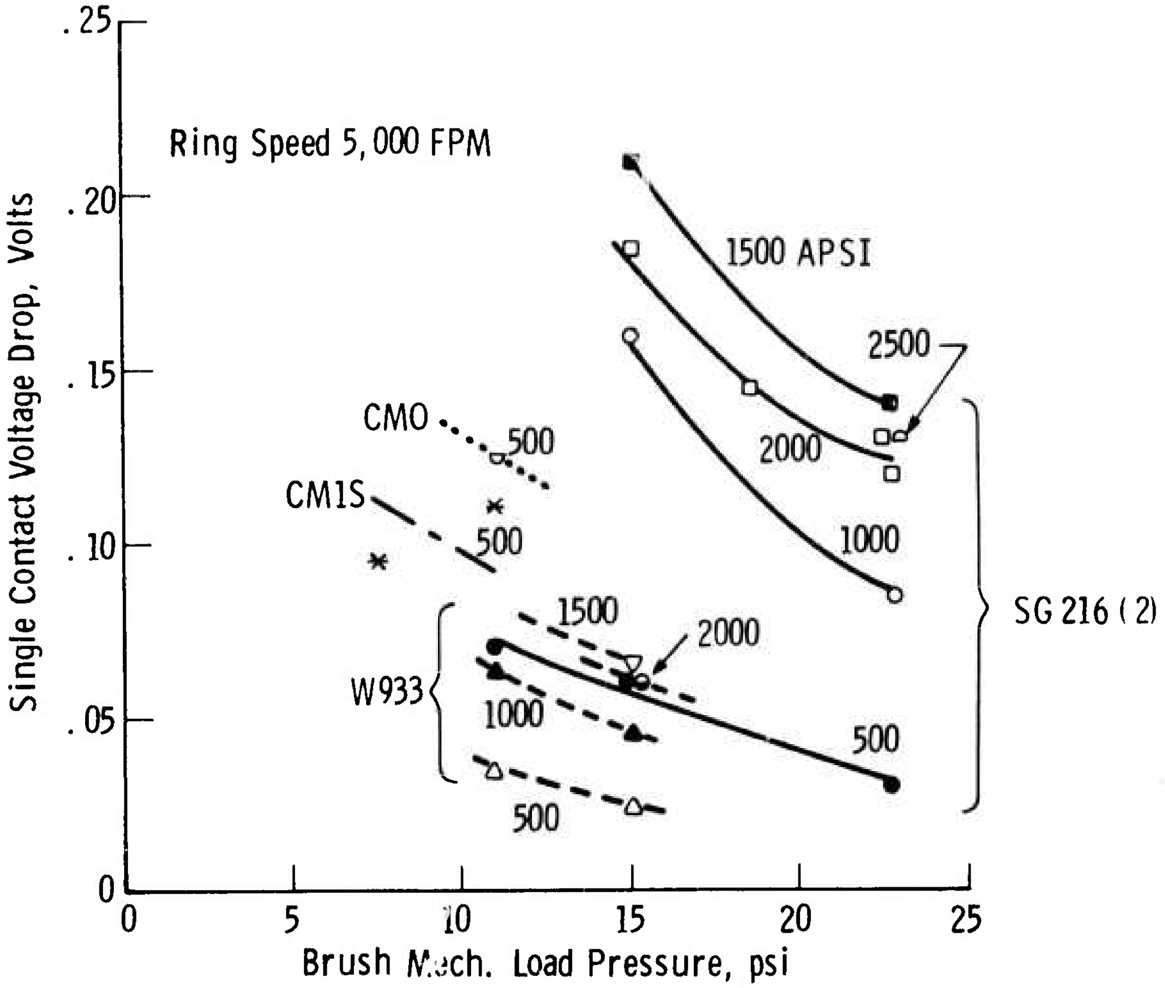


Fig. 2.2.1 Contact Voltage Drop vs Load Pressure for Various Brush Materials.

Curve 683618-A

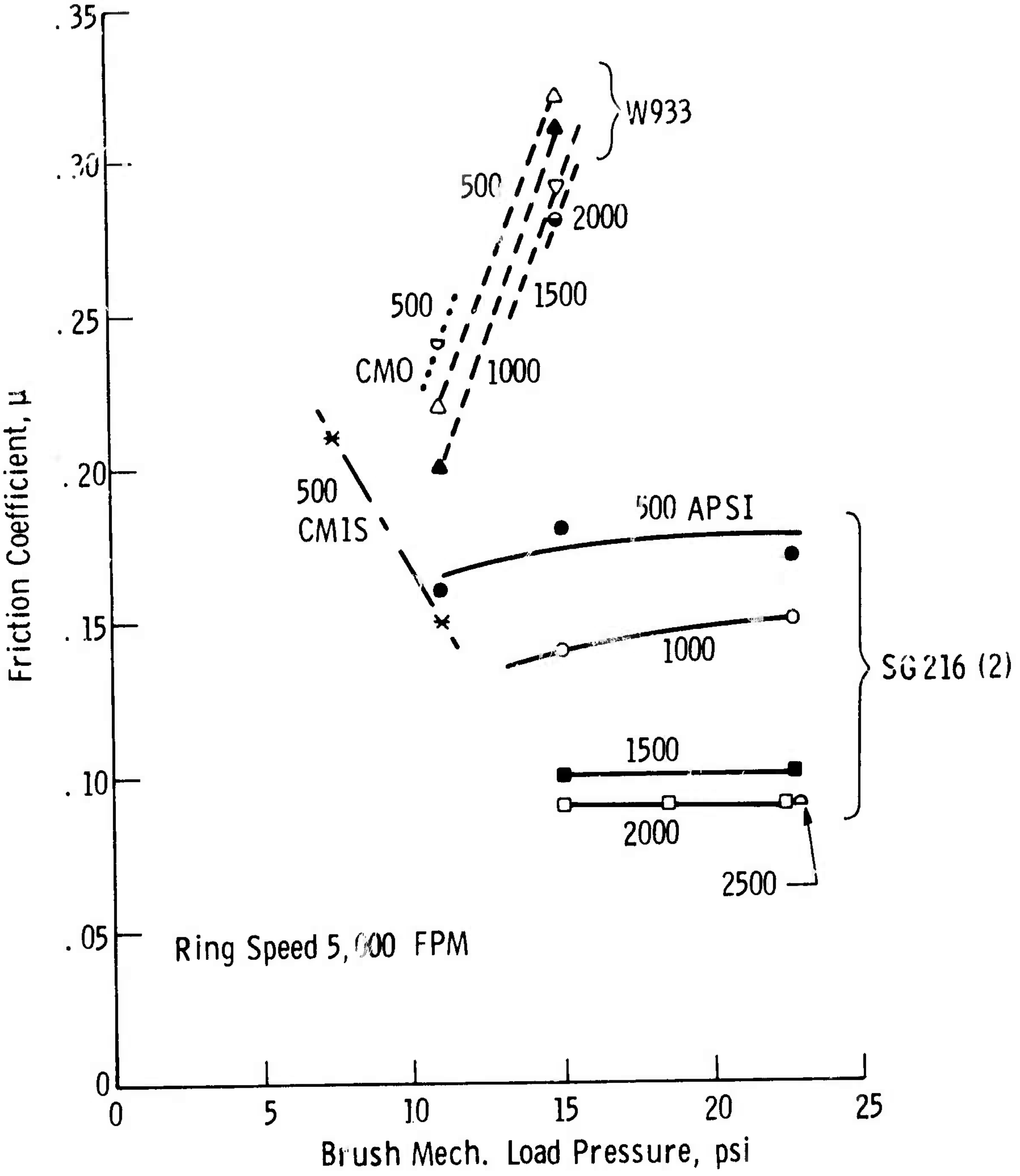


Fig. 2.2.2 Friction Coefficient vs Load Pressure For Various Brush Materials.

Table 2.2.4

Performance Characteristics of Brush Materials (500 A/in^2)
(Medium-High Current Density Applications)

Ring Speed 2500 ft/min

Brush Material	Mech. Pressure lbf/in^2	Single Brush Drop, V	Friction Coef., μ	Power Loss Density, W/in^2	Brush-Holder Temp., °C
W417	10	.14	.15	155	111
W417	10	.24	.11	182	115
W457	10	.41	.05	233	185
SG216(1)	5	.12	.21	119	72
SG216(1)	7.5	.025	.24	115	72
SG216(1)	10	∿0	.26	144	76
SG216(1)	12	0	.26	176	81
SG216(1)	15	0	.22	186	87
SG216(2)	10	.085	.21	161	80
SG216(2)	10	.085	.20	156	80
SG212	10	.06	.16	120	76
SG212	12	.015	.19	137	80
SG212	15	0	.18	153	82
CM3B	10	.32	.08	205	111

2.3 CURRENT COLLECTOR MECHANICAL LOAD SYSTEMS

2.3.1 Objectives

The objective of the mechanical load system program is to develop a system capable of controlling the brush loads to acceptable values. The acceptable values are specified by the Current Collection Contact Material/Performance program that was discussed in Section 2.2. The contact material performance program will determine what is required of the brush system for efficient current transfer and the mechanical load system will determine how to achieve these requirements.

2.3.2 Prior and Related Work

The basic function of a current collection system is to transfer electrical power between stationary and rotating contact members efficiently, reliably, and with long life. Much experience in the application of solid brush current collectors for this purpose has been accumulated over the years at Westinghouse and elsewhere, for brush systems operating at conventional current densities (93 KA/m^2, 60 A/in^2) in ambient air environments. This work has been used as a foundation with the present effort utilized to extend the technology to the high current densities (3.1×10^6 A/m^2, 2000 A/in^2).

2.3.3 Current Progress

The first task was to design a brushholding system suitable for testing high current density brushes. These brushholders were designed for the full-size brush test rigs (HS1 and HS2) described in Section 2.1.1. The basic design philosophy was to utilize existing technology as much as possible in an effort to obtain an immediate test vehicle.

The high power density in the brushholders required water cooling. The cooling water was piped in and out of the brushholders via nominal 3/8 inch copper tubing that also carried the electrical current to and from the brushholders. Before building the test stand a section of copper tubing was subjected to typical testing conditions. The test apparatus consisted of a 3 foot section of nominal 3/8 inch copper tubing with copper blocks attached to each end. One end of the tubing was attached through the use of a nominal 3/8 inch brass "Swagelok" fitting and the other end was attached with soft solder. The conclusions of the test were as follows:

1) The tubing, tube fitting and soldered joint passed current and cooling water acceptably.

2) The nominal design current (400 amps) could be doubled without failure of the circuit in case a current sharing problem would exist in the full size brush test rig.

Figure 2.3.1 is a photograph of the brushholder arrangement used in the HS1 High-Speed Brush Tester. The copper tubing shown at the right transports cooling water as well as current between the brushholder and ground. The main body of the brushholder is machined from two pieces of copper stock. The two pieces are bolted together at the vertical joint that borders the left side of the brush. The test brushes are nominally 5/16 x 5/8 inch cross-section and 1.56 long. The brush is fitted into a rectangular hole (1.0 inch long) that passes through the brushholder and meets the rotor in radial fashion. A nominal 0.06 inch gap exists between the holder and the rotor. The side clearance between the brush and holder averages 0.0025 inch for all four sides. Current is transported between the brush and holder through three flexible shunts made from braided copper cable. Located directly above the brush is the spring holder assembly. The spring loading mechanism consists of a constant force spring attached to an "L" shaped holder. The mechanical load imposed on the brush by the constant force spring can be changed through the use of different springs and/or multiple springs rolled together in an assembly.

The brushholders were utilized in brush screening tests for several months and have presented no apparent problems. Thermocouples were imbedded throughout the holder for a thermal analysis which is discussed in Section 2.4.

Since the brushholders for the HS1 brush test rig worked favorably, a similar system was designed for the Machine-Environment Brush Tester (MEB) described in Section 2.1.2. The basic design philosophy was to design the brushholding system utilizing parts from the HS1 brush test rig. Figure 2.3.2 shows an isometric view of the brushholder arrangement for the Machine-Environment Brush Tester (MEB). The view shows the machine brushholder area with the brush housing cover removed.

The brushholder consists of three copper rings sandwiched together with bolts that tie the holder assembly to the stator conductor drum. The brushholder has been divided into three rings for ease of machining the brush holes accurately. Good electrical contact is maintained between the brushholder and the stator drum when disassembled and reassembled due to silver plating of the contact faces. Also the flange bolt loading for this electrical contact is on the order of 1000 lb/in^2.

The electrical shunts from the brushes are connected to the holder ring that makes contact with the stator conductor drum. The shunts are of equal length and cross-section in order to provide uniform electrical resistance. The shunts are instrumented at typical locations in an effort to investigate current sharing between brushes operating in parallel.

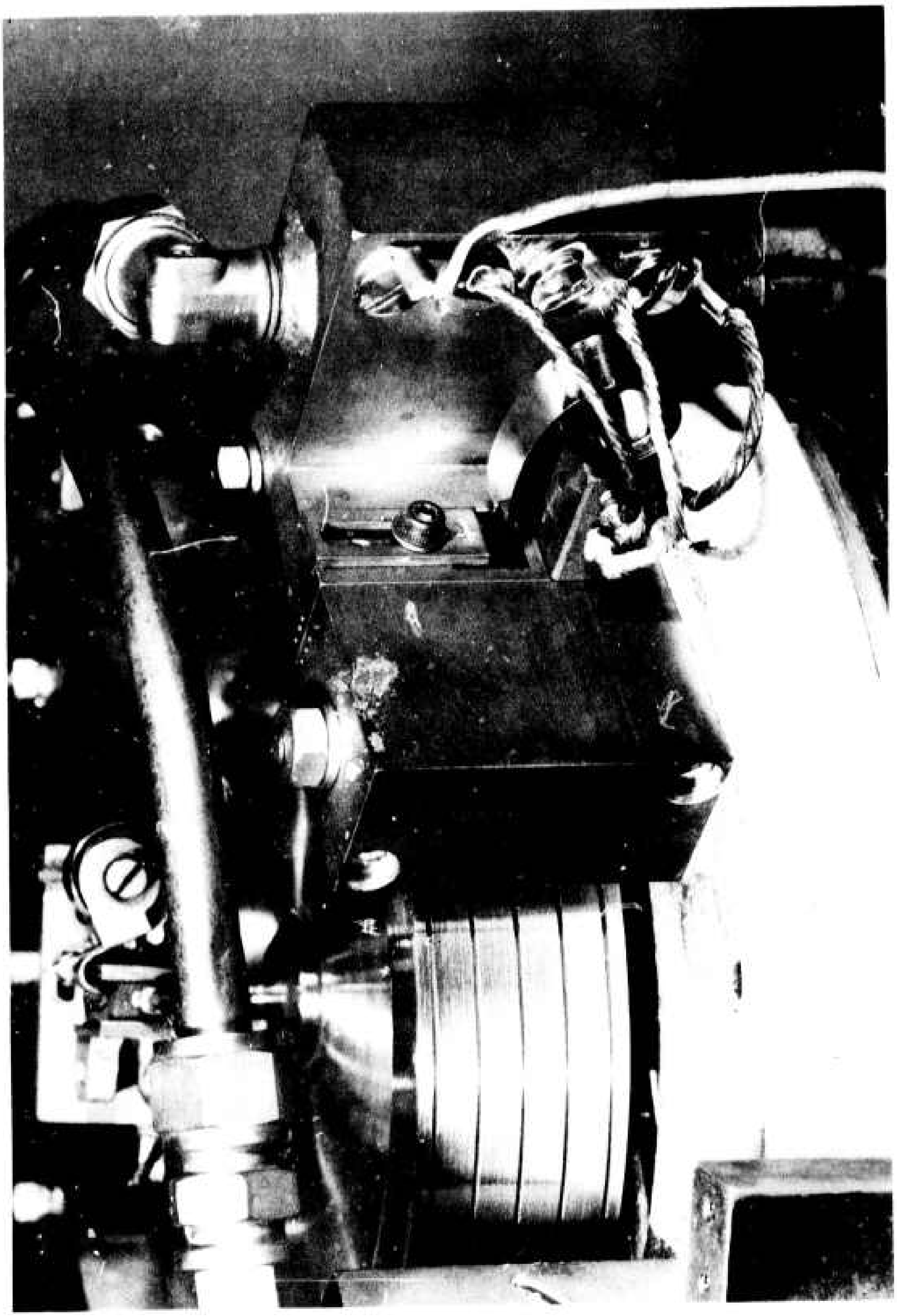


Fig. 2.3.1 Brushholder used in HS1 Brush Test Rig

Dwg. 6371A39

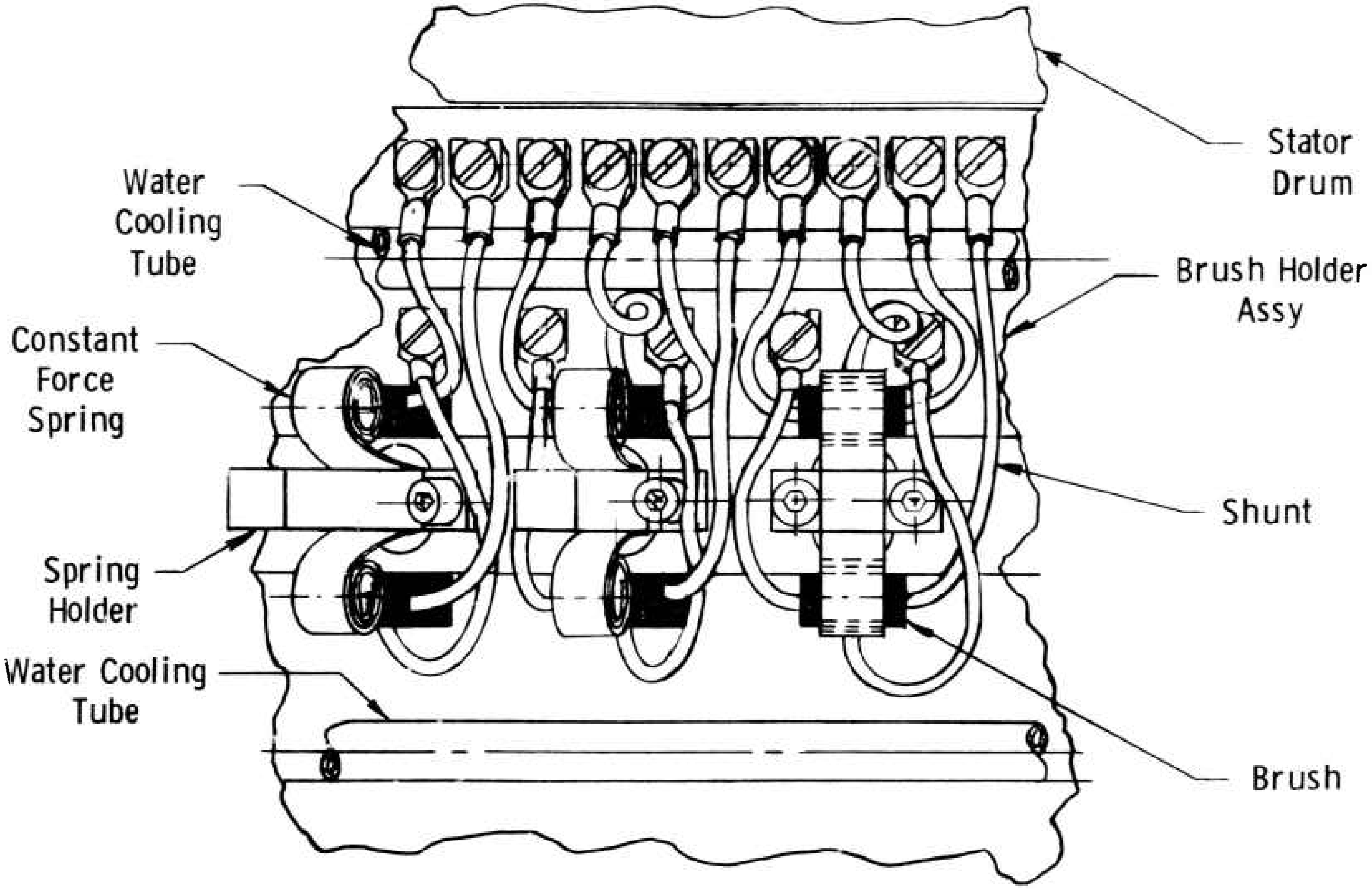


Fig. 2.3.2 Brushholder Arrangement for the Machine-Environment Brush Tester (MEB)

The brushes are fit into rectangular holes in a manner identical to that of the HS1 Brush Tester. The brushes are held in place with constant force springs. The spring holder assembly consists of a metal cross with springs riveted on two opposing sides as shown in Figure 2.3.2. Spare sets of spring holder assemblies utilizing various spring combinations are available for changing brush mechanical loading.

The brushholder is cooled by two circumferential water carrying copper tubes soldered into the brushholder assembly as shown in Figure 2.3.2. Thermocouples were imbedded throughout the holder for a thermal analysis which is discussed in Section 2.4.

2.4 CURRENT COLLECTOR INTERFACE COOLING SYSTEMS

2.4.1 Objectives

The objective of the Interface Cooling System program is to determine the heat transfer characteristics of the high current density brushholders. These heat transfer characteristics will be correlated with the solid brush objectives in order to determine high current density brushholder heat transfer design requirements and procedures.

2.4.2 Prior and Related Work

Westinghouse has accumulated much experience over the years in the application of solid brush current collectors. This experience has been with conventional current densities (93 KA/m^2, 60 A/in^2) where transferring the heat from the brushholder was not considered a problem area. The high current densities (3.1 x 10^6 A/m^2, 2000 A/in^2) increase the power density in the brushholder area to a point where heat transfer has become an area of concern. The intent of the on-going work is to utilize the Westinghouse experience to support the evaluation of the heat transfer in the brushholder area for high current density brushes.

2.4.3 Current Progress

The brushholder heat transfer characteristics of the HS1 Brush Tester and the Machine-Environment Brush Tester (MEB) were analyzed. It was found that the thermal resistance between the brush and the holder was the major thermal barrier of the system. This thermal resistance is complicated and can vary significantly depending on brush position in the holder, clearance, brush loading, geometry, surface finish, material properties and atmospheric properties of the brushholder environment. The brushholders and brushes were instrumented in an effort to determine the thermal resistance. The experimental data was then correlated with theory in an effort to understand the heat transfer mechanism between the brush and holder.

The HS1 Brush Tester was instrumented with thermocouples so that one could determine:

- The heat transfer from the brush in each direction.
- The heat generated in the brush.
- The thermal resistance between the brush and the holder.

This brushholder is described in detail in Section 2.3.3 and shown in Figure 2.3.1.

The heat generated in the brush is due to the mechanical friction at the brush slipring interface and the electrical joule heating from the brush, the shunts and the brush-slipring interface. Heat is transferred primarily from the brush via the shunts, the rotor and the brush-to-brush holder contact. An energy balance yields the heat transferred from the brush to the brushholder, which, with the temperature difference between the brush and brushholder, yields the needed thermal resistance.

The testing apparatus and program were set up and are producing data. Any conclusions at this point would be premature. However, the next report period should provide valuable information for determing the relationship of brush position, clearance, loading, geometry, surface finish, material properties and atmosphere on heat transfer.

Similar thermal instrumentation is designed into the Machine-Environment Brush Tester (MEB), which is described in detail in Section 2.3.3 and shown in Fibure 2.3.2. The major differences with respect to heat transfer between the MEB and the HS1 brush testers are as follows:

- The brushholders in the Machine Environment Tester (MEB) support 48 brushes in two rows (24 in each row). The HS1 tester has one brush for each holder. The multiple brushholder must contend with thermal gradients through the holder yielding variations in temperature between different brushes whereas the single brushholder does not.

- The heat transfer from the brush to the rotor in the HS1 Brush Tester is approximately 1/3 that for the MEB Tester. An increase in heat removed through the rotor reduces the importance of the thermal resistance between the brush and the holder.

The Machine Environment Brush Tester (MEB) is designed to determine the effects of the thermal gradients and the rotor heat transfer. This fully instrumented test rig is currently being assembled and in the next report period, will provide valuable information for the heat transfer analysis.

2.5 CURRENT COLLECTOR GASEOUS ENVIRONMENT/CONTROL

2.5.1 Objectives

The objective of this effort is to provide a controlled gaseous environment in the machine current collector area. Internal pressure, gas purity and moisture content must be controlled.

2.5.2 Prior and Related Work

Work at the Westinghouse Research Laboratories, among others, has indicated the necessity of providing a controlled gaseous environment in the current collector area to prolong brush life.

2.5.3 Current Progress

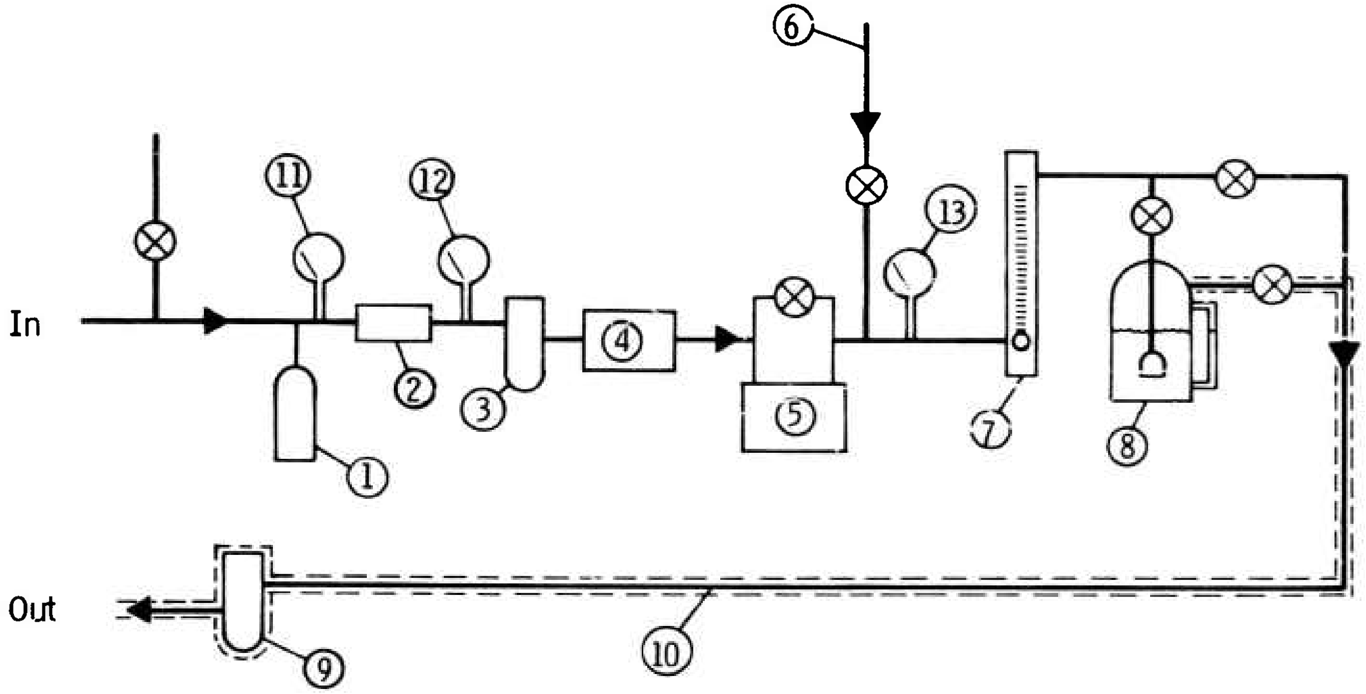
A recirculating gas system for the Machine-Environment Brush Tester (MEB) was designed and constructed. This system will provide a controlled gaseous environment in the machine. Figure 2.5.1 schematically represents the recirculating gas system.

The gas stream exiting the machine first flows through a transparent dust trap where large dirt particles are trapped and can be observed, then it flows through a 60 micron filter for trapping smaller particles. Pressure gauges on each side of the filter allow monitoring its plugging rate. The gas next passes through a probe for determining moisture content, a charcoal filter for removing gaseous impurities, and then into a bellows-type gas pump. From the gas pump, flow is directed through a rotameter-type flowmeter, through a moisturizer (water bubbler) unit, through another moisture probe and finally, back into the machine. Bypass lines, heating tapes, and a pressure regulated gas supply are also included and provide operating flexibility.

The gas system is contained in a portable cabinet measuring 17" x 22" x 69". Mechanical fittings allow connections to be made to the machine and gas supply. The system will circulate gas at the rate of 0-1 CFM and can be pressurized to 15 psig. A Panametrics Model 1000 Hygrometer is used to measure moisture content.

Operation of the system will begin with evacuating the machine and gas system to remove the air, then backfilling with the selected gas. Circulation of the gas will be initiated and a gas sample removed and analyzed. Another pumpdown and/or purge may be required to reduce the impurities to an acceptable level. The gas system will be operated continuously during machine testing, controlling internal machine pressure, moisture content and gas purity.

Dwg. 6370A76



1. Dust Trap
2. 60 µ Filter
3. Moisture Probe
4. Charcoal Filter
5. Bellows Pump
6. Make Up Gas
7. Flow Meter
8. Water Bubbler
9. Moisture Probe
10. Return Gas Line with Trace Heat
11. Pressure Before Filter
12. Pressure After Filter
13. System Pressure

Fig. 2.5.1 Current collection gasecus environment control system for use with the Machine-Environment Brush Tester (MEB)

2.6 REFERENCES

1. Baker, R.M. and Hewitt, G.W., Contact Drop and Wear of Sliding Contacts, AIEE Trans., Vol. 56, pp. 123-28, Jan. 1937.

2. Johnson, J.L. and Moberly, L.E., Brush Life and Commutation in Atmospheres of Air, SF_6, and CO_2, Proc. Electrical Contacts, (1967), pp. 109-16.

3. Rhodenizer, R.L., Development of Solid and/or Liquid Metal Collectors for Acyclic Machines, Final Report for Tasks 1, 2, and 3, Navy Ship Systems Command Report, Contract No. N00024-68-C-5415, February 27, 1970.

SECTION 3

APPLICATION STUDIES

3.1 OBJECTIVES

The purpose of this study is to correlate brush research with machine requirements and potential utilization. This will ensure that the electrical machine requirements, operating parameters, and machine environment effects are effectively translated into the solid brush research program.

3.2 PRIOR AND RELATED WORK

This is a new task. No prior work was performed.

3.3 CURRENT PROGRESS

The range of slipring and commutator peripheral speeds for both motors and generators were initially defined, with a maximum velocity of 250 ft/second for generators.

The range of operating current levels and overload levels were carefully considered with relation to the brush research program.

The problems of loading very high current density brushes to the machine contact surface are complex, and required considerable attention to innovative approaches to shunting and cooling.

The effects of magnetic fields, vibration and other transient effects were carefully considered with reference to the brush loading system.

All of the above requirements were integrated into general schedules of requirements, which are being used by the current collection engineering development and brush research investigators for guidance in those particular efforts.