MASTER

SAN - 679 - 3

DESIGN STUDY

ELECTRICAL COMPONENT TECHNOLOGY FOR
0.25 TO 10.0 MEGAWATT SPACE POWER SYSTEMS

Quarterly Technical Progress Report No. 3

Edited by
A. E. King

May 31, 1967

Aerospace Electrical Division
Westinghouse Electric Corporation
Lima, Ohio

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

UNITED STATES ATOMIC ENERGY COMMISSION • DIVISION OF TECHNICAL INFORMATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

This report has been reproduced directly from the best available copy.

Printed in USA. Price \$3.00. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia 22151.

Quarterly Technical Progress Report No. 3

DESIGN STUDY
ELECTRICAL COMPONENT TECHNOLOGY
FOR 0.25 TO 10.0 MEGAWATT
SPACE POWER SYSTEMS

May 31, 1967

Edited by:

A. E. King
A. E. King, Project Engineer
Liquid Metal Development Section

Approved by:

F. C. Stump
F. C. Stump, Program Manager
Liquid Metal Development Section

N. W. Bucci
N. W. Bucci, Engineering Manager
Systems R & D Department
Aerospace Electrical Division
Westinghouse Electric Corporation

Prepared Under
Contract AT(04-3)-679
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

Aerospace Electrical Division
Westinghouse Electric Corporation
Lima, Ohio

FOREWORD

This Quarterly Technical Progress Report describes work under contract to the United States Atomic Energy Commission from March 1, 1966 to May 31, 1967, on a Design Study of Electrical Component Technology for 0.25 to 10.0 Megawatt Space Power Systems.

The work is directed toward defining representative Rankine nuclear space power electrical systems, the electrical components therein and their development problems. The work was conducted by the Westinghouse Electric Corporation, Aerospace Electrical Division under contract AT (04-3)-679 administered by the USAEC San Francisco Operations Office. Technical liaison is maintained with the USAEC Division of Space Nuclear Systems, Washington, D. C., Mr. G. S. Leighton, Liaison Officer, and with the Reactor Division of the San Francisco Operations Office, Mr. F. W. Hunton, Liaison Officer.

Members of the Westinghouse Systems Research and Development Department assisting in the preparation of this report, include A. E. King, T. C. Allen, D. R. Basel, C. L. Doughman, J. W. Gyurek, J. G. Hoop, R. D. Jessee, C. C. Kouba, J. L. McCabria, and E. F. Swiderski

BLANK

ABSTRACT

Progress on parametric studies to determine minimum system weight as a function of electrical component rating, voltage, frequency, and speed are presented on a-c generators, a-c motors, power conditioning, and power distribution equipment for 0.25 to 10.0 megawatt space nuclear electric power plants utilizing the Rankine conversion cycle. The power conditioning and distribution equipment includes transformers, rectifiers, frequency changers, contactors, and transmission lines. Concluding parametric data is presented for the electrical system components listed. Electrical power systems are presented to illustrate electrical load breakdown on probable missions requiring 0.25 to 10.0 megawatts of power. Progress on experiments to verify analytical techniques for inductor generator designs typical of high-power, high-speed, high-frequency, high-temperature applications is presented.

CONTENTS

1.	SUMMARY	1
1.1	Events of the Period	2
1.2	Plans for Coming Period	3
2.	PARAMETRIC SCREENING STUDIES	4
2.1	Generator Parametric Study	4
2.2	AC Motor Parametric Study	9
2.3	Frequency Changer Study	22
2.4	Power Conditioning Study.....	28
3.	SYSTEM DEFINITIONS	53
3.1	Nuclear Mechanical Systems	53
3.2	Electrical System Definition	59
4.	EXPERIMENTAL VERIFICATION	69
4.1	Magnetic No-Load Loss Tests	69
4.2	Rotor Cooling Concepts	73
	REFERENCES	74
	APPENDIX A	76
	APPENDIX B	83
	APPENDIX C	92

FIGURES

2.1	AC Motor Parametric Study	11-19
2.3-1	Gas Tube Frequency Changer Parametric Data ...	24
2.3-2	Gas Tube Frequency Changer Parametric Data ...	27
2.4-1	Rectifier Parametric Data	35
2.4-2	Rectifier Parametric Data	36
2.4-3	Rectifier Parametric Data	37
2.4-4	Rectifier Parametric Data	38
2.4-5	Three Phase Transformer Parametric Data	41
2.4-6	Three Phase Transformer Parametric Data	42
2.4-7	Three Phase Transformer Parametric Data	43
2.4-8	Three Phase Transformer Parametric Data	44
2.4-9	Three Phase Transformer Parametric Data	45
2.4-10	Single Phase Transformer Parametric Data	46
2.4-11	Single Phase Transformer Parametric Data	47
2.4-12	Single Phase Transformer Parametric Data	48
2.4-13	Single Phase Transformer Parametric Data	49
2.4-14	Single Phase Transformer Parametric Data	50
2.4-15	Single Phase Transformer Parametric Data	51
3.1-1	Manned Vehicle Shield Weights	56
3.1-2	Unmanned Vehicle Shield Weights	57
3.1-3	Turbine Shaft Power Specific Weight	58
3.2-1	Preliminary Concept No. 1 for Unmanned Scientific Probe	60
3.2-2	Preliminary Concept No. 1 for Manned Interplanetary Mission	61
3.2-3	Concept 1 - Electric Engine Module	62
3.2-4	Preliminary Concept No. 1 Synchronous Orbit Space Station	63
3.2-5	Preliminary Concept for Lunar Base	64
3.2-6	Multiple Power Source Concept of Achieving a Specific Rating	66
3.2-7	Single Line Diagram of Isolated-Load Bus System	68
4.1-1	Rotor Pole Face Slotting Operation	70
4.1-2	Slotted Rotor Pole Faces	71
4.1-3	Ultrasonic Inspection of Rotor	72
A-1	Types of Brazed Specimens in SNAP 50/SPUR Program	78
A-2	Set of Thin-Wall (0.090-inch) Ceramic Components For Prototype SNAP-50/SPUR Generator's Stator Bore-Seal Assembly	79
A-3	Thermal Expansion of Ceramic and Metal Bore-Seal Components	81
B-1	Commutation in Rectifier Circuit When Operating with Phase Control	84
B-2	Cycloconverter Output Voltage Showing Phase Delay in Switching	86

TABLES

2.1	Summary of Most Favorable AC Motor Design Parameters at End of Parametric Study	10
2.3-1	Thyratron-Tube-Type Cycloconverter	25
2.4-1	120 Volt DC Silicon Diode Rectifier Assembly System	29
2.4-2	30 Kilovolt DC Silicon Diode Rectifier Assembly System	30
2.4-3	1000 Volt DC Gas and Vapor Tube Diode Rectifier Assembly System	32
2.4-4	5000 Volt DC Vapor Tube Diode Rectifier Assem- bly System	33
2.4-5	30,000 Volt Gas Tube Diode Rectifier Assembly Rectifier	34
2.4-6	Gas and Vapor Tube Diode Rectifier System Parametric Data	39
3.1-1	Powerplant Component Weights	54
3.1-2	Average Ratio of Total System Specific Weights at 40,000 and 10,000 hours	55
B.1	Thyristor Constants used in Dynamic Computations	89

1. SUMMARY

The Aerospace Electrical Division of the Westinghouse Electric Corporation has been under contract to the United States Atomic Energy Commission since September 1, 1966 to define conceptual designs of complete electrical power systems and the electrical components therein which are suitable for Rankine nuclear space power systems in the 0.25 to 10.0 megawatt range. Three representative missions- interplanetary, planetary, and orbital - have been specified in order that the conceptual definitions consider dependent design parameters typical of actual flight conditions. Work is being carried on in design studies and in associated analytical verification experiments.

The design studies are being carried out in two successive stages: (1) analytical screening studies to establish parametric data, optimum designs and design limitations for four power levels, and (2) design studies of selected configurations to determine the best conceptual design at each power level and the development problems associated with them. The electrical system components being studied are a-c generators, a-c motors, frequency changers, power conditioning equipment, power transmission and control equipment, and electrical system control and protection equipment. The results of the studies will be applicable to: (1) defining the component development effort required to realize mission capabilities, and (2) aiding the electrical system designer and nuclear system planner in specifying the optimum electrical configuration for specific missions.

The analytical verification experiments are being carried out to evaluate the adequacy of certain analytical techniques for a-c generator design. The experiments are specifically directed toward evaluating magnetic unbalance forces, magnetic flux distributions, generator losses at no-load conditions, and rotor coolant flow concepts.

The scope of the Design Study is summarized in the following table in order for the reader to better understand the extent of the work being carried out and the relationships of the various work described in the following sections. There are three major tasks which contain a total of twelve separate but closely interrelated sub-tasks.

Summary of Design Study Tasks

Parametric Screening Studies

- Power Uses and Missions Definition
- Nuclear-Mechanical System Definition
- Generator Parametric Study
- AC Motor Parametric Study
- Frequency Changer Parametric Study
- Power Conditioning Parametric Study
- Power Transmission and Distribution Study

Conceptual Design Analyses

- Electrical System Definition
- Conceptual Design Analysis and Layout

Experimental Verification (generator only)

- Experimental Evaluation of Magnetic Unbalance Forces and Flux Distribution
- Experimental Evaluation of No-Load Losses
- Experiments Associated with Rotor Cooling Concepts

1.1 Events of the Period

The Parametric Screening Studies were completed and work was begun on the Conceptual Design Analyses. Work continued on preparation of the rotor and stator components for the No-Load Dynamic Tests. The Rotor Coolant Flow Experiments were completed. The status of the individual sub-tasks are summarized below.

The Power Uses and Missions Definition task was previously completed and summarized in the 2nd Quarterly Report⁽²⁾*.

The Nuclear Mechanical System Definitions task was completed and is summarized in this report. The results indicated that the systems for 40,000 hours life were from 10 to 70 percent heavier than those for 10,000 hours. In addition, the 800°F electrical system coolant temperature gave the lightest system specific weight of the three temperatures examined.

The Generator Parametric Study was completed and the results are tabulated within. In general, the results of the second cycle screening study indicated that the most desirable frequencies were between 2000 and 800 Hz and the most desirable speeds were between 40,000 rpm and 5333 rpm as rating and temperatures increased respectively. The most desirable voltage was 500 volts line-to-neutral for all conditions.

* Superscripts in parenthesis refer to References in end of report.

The Motor Parametric Study was completed and the results are tabulated within. The results indicated that the most desirable frequencies were between 400 and 800 Hz, the most desirable speeds were between 24,000 and 8,000 rpm. The most desirable voltages were generally 120 volts but in some instances were as high as 1000 volts.

The Frequency Changer Parametric Study was completed with the design of three high-temperature gas-tube rectifiers in place of the solid state devices. Additional calculations were made to check previously approximated thyristor loss calculations.

On the Power Conditioning Parametric Study, the analyses of rectifier designs were completed, both on the solid state devices and on seven gas-tube rectifiers. Data is presented on these remaining rectifiers. The analyses of transformer designs were nearly completed and typical data are plotted within.

The Power Transmission and Distribution Study was completed.

The Electrical System Definition and Conceptual Design tasks are well underway with some conceptual design layouts already completed on the frequency changers and rectifiers. The basic electrical systems defined for the specified missions are summarized within.

The Experimental Verification Tests were completed with the exception of the No-Load Loss Dynamic Tests scheduled to begin in June. The Rotor Coolant Flow Experiments verified the design of the particular rotor flow configuration as predicted.

1.2 Plans for Coming Period

Topical reports will be completed on the parametric studies of the generator, motor and power conditioning equipment. The latter will include the parametric study data on the frequency changer and power transmission and distribution study in addition to the transformers-rectifiers.

Conceptual design layouts will be completed on four ratings each of the generators, motors, frequency changers, transformers, and rectifiers. The particular ratings selected for the designs will be according to the results of the Electrical System Definitions task. Documentation of the Conceptual Designs will be included in the Final Report in addition to the various definition study results.

The No-Load Loss Dynamic Tests will be completed and the results included in the Verification Test Topical along with results of the static tests and rotor flow tests.

2. PARAMETRIC SCREENING STUDIES

2.1 Generator Parametric Study

2.1.1 Summary of Past Quarter

During the third quarter, approximately 670 generator designs were computed and compared in terms of generator electrical weight and powerplant and cooling system weight penalties to determine the best range of frequencies, speeds, and voltages for ratings of 0.4 mva, 1.2 mva, 6 mva, and 12 mva at coolant temperatures of 500, 800, and 1100°F. The parametric study was performed in two cycles. The basic purpose of the first cycle study was to screen out parametric combinations which result in designs exceeding material limitations and to establish the feasibility of the initial material and parametric choices. Results obtained on the first cycle designs were used in the second cycle study to more specifically determine the best combinations of frequency, speed, and voltage for the specified ratings and coolant temperatures. Calculation of parametric design points for the second cycle studies has been completed and the data is presently being analyzed. Preliminary results of the second cycle studies are presented in tabular form in the following sections of this report.

The designs at each temperature and rating are compared on the basis of generator electromagnetic weight alone and electromagnetic weight in combination with a system weight penalty which is determined from the generator efficiency and the specific weights of the power plant and cooling systems that supply and dissipate the losses. The choice of optimum system parameters is based on minimum system weight.

2.1.2 Technical Discussion

A. Second Cycle Generators Design Studies

1. Frequency Study - A frequency study was conducted by calculating generator designs combining the following parameters:

Generator Rating (mva)	Coolant Temp. (°F)	Volts	RPM	Frequency Points (Hz)
0.4	500	500	30000	1000,1500,2000,2500,3000
1.2	&	500	24000	800,1200,1600,2000,2800
6.0	800	500	12000	800,1200,1600,2000,2800
12.0		1000	10000	833,1000,1165,1500,2000
0.4	1100	500	12000	800,1000,2000,2800,3200
1.2	1100	500	10000	500,1000,2000,2500,3000
6.0	1100	500	8000	400, 800,1200,1600,2000
12.0	1100	1000	6000	400, 800,1200,1600,2000

The selections of voltage and speed were based on results of the first cycle parametric studies; frequency points correspond to integral numbers of pole pairs.

Rotor material is for coolant temperatures of 500° and 800°F, H-11 (AMS 6487) magnetic alloy and an experimental magnetic alloy* for the 1100°F coolant temperature. Stator materials are presented in Reference 1. Results from the first cycle designs indicated the 1100°F designs exceeded the stress limits of the NIVCO rotor material at all but unreasonably low speeds. Magnetic alloy H-11 (AMS 6487), which proved to be superior to NIVCO for the 800°F coolant temperature, could not be used at the 1100°F coolant temperature because of high temperature strength limitations. The experimental alloy proved to be superior to NIVCO for the 1100°F coolant temperature with regard to high temperature strength and flux carrying capability.

The following optimum generator frequencies were selected from results of the second cycle frequency study based on minimum system weight.

Generator Rating (mva)	Coolant Temp. (°F)	Frequency (Hz)
0.4	500	2000
1.2	&	1600
6.0	800	1200
12.0		1200
0.4	1100	1500
1.2	1100	1200
6.0	1100	800
12.0	1100	800

2. Speed Study - Following the frequency study, a speed study was conducted combining the following parameters and using the above best frequencies from the frequency study.

* Precipitation hardened cobalt base alloy (alloy 1BS1) being developed by Westinghouse Electric Corp., contract NAS3-6465 for the NASA, Lewis Research Center, composition is Co-15Ni-5Fe-5Ta-0.2Ti-1.25Al.

Generator Rating (mva)	Coolant Temp. (°F)	Volts	Freq.	RPM
0.4	500	500	2000	15000, 20000, 24000, 30000, 40000
1.2	500	500	1600	12000, 16000, 19200, 24000, 30000
6.0	500	500	1200	9000, 10286, 12000, 14400, 18000
12.0	500	1000	1200	6000, 8000, 10286, 12000, 14400
0.4	800	500	2000	15000, 20000, 24000, 30000, 40000
1.2	800	500	1600	12000, 16000, 19200, 24000, 32000
6.0	800	500	1200	7464, 6092, 5318, 4463, 3864
12.0	800	1000	1200	4000, 6000, 8000, 9000, 10286
0.4	1100	500	1500	10000, 11250, 12857, 15000, 18000
1.2	1100	500	1200	8000, 9000, 10286, 12000, 14400
6.0	1100	500	800	5333, 6000, 6857, 8000, 9600
12.0	1100	1000	800	3200, 4000, 4800, 5333, 6000

In general, both generator electromagnetic weight and system weight decreased with increasing speed over the speed ranges investigated with the rate of weight decrease becoming smaller at the higher speeds. Optimum speeds were selected on the basis of minimum system weight within the stress limitations of the rotor material at the operating temperature of the rotor.

The following generator speeds were selected from results of the second cycle speed study.

Generator Rating (mva)	Coolant Temp. (°F)	RPM
0.4	500	40000
1.2	500	24000
6.0	500	12000
12.0	500	12000
0.4	800	30000
1.2	800	19200
6.0	800	12000
12.0	800	8000
0.4	1100	18000
1.2	1100	12000
6.0	1100	6857
12.0	1100	5333

3. Voltage Study - Following the frequency and speed studies, a voltage study was conducted by calculating designs and combining the following parameters, using the frequency and speed combinations found best from the foregoing studies.

Generator Rating (mva)	Coolant Temp. (°F)	Freq.	RPM	Volts
0.4	500	2000	40000	500,1000,1500,2140
1.2	500	1600	24000	500,1000,1500,2140
6.0	500	1200	21000	500,1000,1500,2140
12.0	500	1200	12000	500,1000,1500,2140
0.4	800	2000	30000	500,1000,1500,2140
1.2	800	1600	19200	500,1000,1500,2140
6.0	800	1200	12000	500,1000,1500,2140
12.0	800	1200	8000	500,1000,1500,2140
0.4	1100	1500	18000	500,1000,1500,2140
1.2	1100	1200	12000	500,1000,1500,2140
6.0	1100	800	6857	500,1000,1500,2140
12.0	1100	800	5333	500,1000,1500,2140

For all ratings except the 1.2 mva rating, system weight increased with voltage for the range of 500 volts to 2140 volts. For the 1.2 mva rating, system weight was minimum at 1000 volts with a slight increase in system weight at 500 volts. In general, system weight was not a strong function of voltage in the range of 500 volts to 1500 volts. Five hundred volts was selected for all combinations of mva rating and coolant temperatures.

4. Summary of Parametric Combinations - Table 2.1.1 summarizes the parametric combinations resulting from a preliminary analysis of the design data.

Table 2.1.1 Summary of Parametric Combinations

Generator Rating (mva)	Coolant Temp. (°F)	Frequency (Hz)	Speed (rpm)	Volts
0.4	500	2000	40000	500
1.2	500	1600	24000	500
6.0	500	1200	12000	500
12.0	500	1200	12000	500
0.4	800	2000	30000	500
1.2	800	1600	19200	500
6.0	800	1200	12000	500
12.0	800	1200	8000	500
0.4	1100	1500	18000	500
1.2	1100	1200	12000	500
6.0	1100	800	6857	500
12.0	1100	800	5333	500

2.1.3 Plans for Coming Quarter

Analysis of second cycle parametric design cases will be completed. Results of the studies will be presented in curve form. A topical report will be prepared which documents the events and conclusions of the Generator Parametric Screening Study.

Two designs which are representative of the optimum designs and which have hot-spot temperatures in excess of 1100°F will be analyzed using advanced (1500°F) materials. Possible weight and efficiency benefits will be examined. One design which is representative of the optimum designs will be analyzed using 1400°F coolant and corresponding high temperature materials for possible weight and efficiency benefits.

Conceptual design layouts will be prepared for four representative ratings over the 0.4 to 12.0 mva range.

2.2 AC Motor Parametric Study

2.2.1 Summary of Past Quarter

The a-c motor parametric study was completed. Collection, review, and display of data was begun. Second cycle voltage studies were not required for any of the 500, 800, and 1100°F coolant studies and in some instances, particularly the 500°F coolant designs, it was possible to terminate the second cycle studies with the second cycle frequency studies. Table 2.1 summarizes the results of the parametric study at the conclusion of all studies performed i.e., wherever terminated. This occurred, as mentioned above, in some cases with the second cycle frequency study and in some cases with the second cycle speed study. These individual terminal points for specific motor ratings and coolant temperatures are defined in the following paragraphs.

The frequency, speed, and voltage combinations displayed for the various motor ratings and coolant temperature combinations in Table 2.1 should be interpreted as indicating broad, general trends and not as optimum motor design parameters. Other parameters must be weighed in conjunction with these parameters (frequency, speed, and voltage) when choosing a motor design for a particular application. For example, the system designer would certainly desire to consider power factor when choosing a motor to be integrated into a system. Temperature is another important parameter; the results of thermal analysis are not directly reflected in the data contained in Table 2.1. Collection and review of all the parametric data, which is being performed currently, will permit conclusions to be formed about definite motor trends. These conclusions are being reserved for the final topical report in conjunction with a more comprehensive display of parametric data.

Figure 2.1 displays diagrammatically the course of the parametric study. The values shown between the blocks for each study represent input parameters which were selected from the previous study and held constant (except in the second cycle speed studies) in the subsequent study. The top value is the parameter associated with the best design chosen in the previous study. The lower value represents the remaining parameter held constant in the previous study and carried over as a constant in the subsequent study.

Electrical weight and efficiency were used as a basis for choosing the best frequency, speed, or voltage. Where these parameters were opposed (i.e., where a choice between two designs was involved, one with lowest weight and one with highest efficiency), preliminary system weight penalties were used to determine the choice. Where two or more designs were so similar as to make a choice difficult, detailed thermal analyses were performed in an attempt to sufficiently amplify inherent differences in efficiencies. Application of the system weight penalty was also used in these situations as an alternative. In one case -

Table 2.1 Summary of Most Favorable AC Motor Design Parameters
at End of Parametric Study

500°F COOLANT					
Rating (HP)	Frequency (Hz)	Voltage (Volts L-N)	Synchronous Speed (rpm)	Specific Electrical Weight (a) (lbs./HP)	Efficiency (percent)
5	400	120	24000	1.88-2.39	72.5-76.8
30	400	120	12000	1.03-1.17	82.6-83.9
60	400	120	12000	0.825-0.94	85.0-88.8
100	400	120	12000	0.825-0.84	85.3-86.8
250	400/600	240	8000	0.601-0.729	88.0-88.5
800°F COOLANT					
5	400	120	24000	2.39-2.41	70.4-72.5
30	400	120	12000	1.33-1.435	74.3-77.4
60	800	120	24000	0.517-0.618	83.1-83.8
100	800	1000	24000	0.556-0.583	83.1-85.7
250	600	480	9000	0.673-0.752	85.4-87.5
1100°F COOLANT					
5	400	120	24000	2.85-2.91	62.6-63.1
30	600	240	18000	0.998-1.02	76.1-76.4
60	600	240	18000	0.745-0.758	80.7-81.4
100	600	240	18000	0.77-0.782	82.0-83.7
250	600	480	18000	0.487-0.523	86.8-87.5
(a) Based on horsepower rating corresponding to Torque = $\frac{\text{Max. Torque}}{2.25}$					

1. 5 HP

2. 30 HP

Figure 2.1

AC Motor Parametric Study
500°F Study

3. 60 HP

4. 100 HP

Figure 2.1 - Continued
AC Motor Parametric Study
500°F Study

5. 250 HP

Figure 2.1 - Continued
AC Motor Parametric Study
500°F Study

1. 5 HP

2. 30 HP

Figure 2.1 - Continued
AC Motor Parametric Study
800°F Study

3. 60 HP

4. 100 HP

Figure 2.1 - Continued
AC Motor Parametric Study
800°F Study

5. 250 HP

Figure 2.1 - Continued
AC Motor Parametric Study
800°F Study

1. 5 HP

2. 30 HP

Figure 2.1 - Continued
AC Motor Parametric Study
1100°F Study

3. 60 HP

4. 100 HP

Figure 2.1 - Continued
AC Motor Parametric Study
1100°F Study

5. 250 HP

Figure 2.1 - Concluded
AC Motor Parametric Study
1100°F Study

the 500°F, 250 HP designs - all of these methods failed to produce any significant differences between the 400 and 600 Hertz designs; therefore, both frequencies are indicated.

Examination of Figure 2.1 will reveal why it was possible to delete portions of the second cycle studies from the total parametric study. Whenever a particular second cycle study resulted in a combination of parameters which matched the best parameters from previous studies, there was obviously no advantage in continuing further.

Approximately at the time of initiation of the 800°F and 1100°F first cycle voltage studies, it became apparent that the second cycle frequency studies must be initiated at once to permit completion of the 800°F and 1100°F studies on a timely basis. Based on results of the previous studies, the number of frequencies to be studied in the second cycle frequency studies was reduced from six to three (400, 600, 800 Hertz), and the results of the first cycle voltage studies were assumed or anticipated to indicate 120 volts. The 800°F - 5, 30, 60, and 100 HP design and the 1100°F - 5, 30, and 60 HP design second cycle frequency studies were initiated on this basis in parallel with the first cycle voltage studies. As shown in Figure 2.1, for all but one of the 800°F designs and one of the 1100°F designs, the voltage assumptions proved correct. For those designs when the voltage changed, the new voltage was used as an input to the second cycle speed studies when run. The frequency studies with the incorrect voltages were not rerun, however. This will not affect the resulting trends shown by the second cycle frequency studies, and the actual magnitudes of the weights and efficiencies may be corrected to new values corresponding to the new voltages using first cycle data. The broken lines in Figure 2.1 indicate where the voltage studies were by-passed so that the frequency studies could be performed in parallel.

Theoretically, the synchronous speed should be held constant at the speed determined by the first cycle speed studies throughout the second cycle frequency studies. However, permissible numbers of pole-frequency combinations did not permit matching the speed to input speeds for every frequency. Alternatively, for those frequencies not permitting the exact desired speed, the number of poles were chosen so that the nearest possible speed to the desired speed was obtained. When the difference between a higher speed and the desired speed and the difference between a lower speed and the desired speed were about equal, the higher speed was usually chosen because previous data had, in general indicated that the higher speeds produced the better designs.

Detailed temperature calculations were run on selected designs throughout the parametric study to act as a guide in determining the most favorable designs. In most instances, thermal instability or excessively high temperatures were used as justification for eliminating designs from consideration. However, there were exceptions where the results of the computer design thermal program were disregarded. For example, an 800 Hz, 12000 rpm design

was chosen as the best design in the 1100°F - 100 hp first cycle frequency study. In the first cycle speed study all 1100°F - 100 hp designs at speeds greater than and including 12000 rpm were thermally unstable*. Because of slight design differences which were inadvertently incorporated in the process of design iteration between the first cycle frequency and the first cycle speed studies, the designs were just different enough to cause one to cool and the other to become thermally unstable. The thermal instability of the speed study 12000 rpm - design indicated by the computer was ignored and 12000 rpm was chosen as the best speed.

Another example involved the 1100°F-250 hp designs. Based on initial design temperature estimates and other internal design factors held common between all the parametric designs to provide a common basis for comparison, none of the 1100°F-250 hp first cycle frequency study designs were thermally stable when detailed temperature calculations were made. Rather than revising the design temperatures and doing the study over, the results of the detailed thermal analysis were ignored and the studies continued on the basis of the best of the designs using the original design temperature estimates. Throughout the 1100°F-250 hp studies, selected designs were adjusted until they did become thermally stable to determine cooling weight penalties. These designs were generally 20 to 50 pounds heavier, but less than 1.0 pound heavier on a specific weight basis - pounds per horsepower output.

2.2.2 Plans for Coming Quarter

The data obtained from the parametric analysis will be collected, condensed, and displayed in the form of appropriate curves and tables so that significant trends can be identified and explained.

The a-c motor topical report will be prepared and published.

Conceptual design layouts will be prepared for four representative ratings.

* Thermally unstable means that the computer design program failed to reach a steady-state temperature distribution within an allowable number of design iterations. Additional iterations were not made to limit the amount of detail design calculations made on the parametric screening designs. The designs are still valid with the approximate temperatures calculated.

2.3 Frequency Changer Study

2.3.1 Summary of Past Quarter

In the original parametric study completed in the second quarter, thyristor losses were estimated in order to complete the parametric comparative calculations. In the present quarter, the thyristor losses were recalculated by a more accurate method to verify the original estimates.

Three tube-type frequency changer designs were also completed during the third quarter.

2.3.2 Thyristor Loss Recalculation

Parametric data covering frequency changer (cycloconverter) designs were presented in the Second Quarterly Report(2). Thyristor loss calculations were made in two parts: (1) conduction losses and (2) switching losses. Conduction losses were made by calculating the average value of current in the thyristor, estimating the equivalent current wave form relative to published data, and reading the average dissipation from the appropriate curve in the manufacturer's data sheet. The published curves cover source frequencies up to 400 Hz. Since the source frequencies covered in the parametric study were as high as 3200 Hz, it was necessary to consider switching losses in the thyristor. In the parametric study, it was assumed that the thyristor voltage would fall at some constant rate. The losses were estimated by calculating the volt-ampere-seconds during an average turn-on period and multiplying this value by the number of switching operations per output cycle.

Although the expected switching losses were small, it was felt that the values should be verified by a more accurate method of computation. A method was, therefore, developed which considers the dynamic characteristic of the thyristor in computing losses. This method is described in Appendix B.

Losses were recomputed for several design ratings. The thyristor losses were generally slightly higher than the original calculations shown. The resulting increase in overall cycloconverter losses was on the order of 10 percent and less. In no case is the change in losses great enough to warrant a change in weight of a unit. The percent increase in losses would require a corresponding percent increase in coolant flow rate shown in Figures 2.3-8, 2.3-9, and 2.3-10 of the Second Quarterly Report. Tabulated on the following page are the check points computed showing the increase in losses over the original calculation.

Rating		Table No. (Second Quarterly Report)	Thyristor Loss		Net Change Per Thyristor (watts)	Percent Change In Total Loss
KVA	Input Frequency (Hz)		Original Calculation (watts)	Recal- culation (watts)		
25	2000	2.3-1	19.5	21.3	1.8	6.64
50	2000	2.3-1	43.3	46.5	2.8	5.4
100	2000	2.3-1	72	78.3	6.3	7.35
250	2000	2.3-1	75.1	84.4	9.3	10.2
50	800	2.3-4	42.2	43.6	1.4	2.5
50	3200	2.3-7	45.2	50.5	5.3	10.5

2.3.3 Gas or Vapor Tube Cycloconverter

A. Electrical Design - Although development work is being done on gas and vapor tubes, tubes suitable for use in the cycloconverters of this study are not available. Weight and efficiency calculations have been made, however, based on the best estimates available. Power circuits used are the same as for the silicon-thyristor cycloconverters reported in the Second Quarterly Report. It was assumed that the control circuits used in the silicon-thyristor designs would be suitable for the tube-type design, provided an amplifier stage were added for each tube firing circuit. Control weight, which is not very significant, was estimated for each design based on the power required to fire the tube.

Three ratings were considered in the study; 5, 50, and 500 kva. Tube ratings, weight and dimensions were obtained from General Electric Company, Electronic Components Division, for each of the three ratings. The data for these tubes were calculated and include a safety factor for withstanding normal transients in voltage and current expected in operation. No further derating was included, unlike the case with the silicon-thyristor designs. Though complete specifications are not available for the tubes, the major characteristics are listed in Table 2.3-1.

Eighteen tubes are required for each three-phase cycloconverters (six per output phase). Each pair of tubes is connected between the high-frequency source and the load phase through a small inductor. No transformer or filter is included. The power circuit is the same as shown in Figure 2.3-1 of the Second Quarterly Report except that the controlled rectifiers are replaced by thyatron tubes.

Weight and efficiency of tube-type cycloconverters are shown in Figure 2.3-1. These curves are based on calculations made for the three selected ratings (5, 50, and 500 - kva) operating at 400 cps output from a 3-phase, 200-volt, 2000-Hz source. Comparison of the curves to those of the thyristor designs shows that the tube-type units are considerably heavier and less efficient.

Figure 2. 3-1

Gas Tube Frequency Changer Parametric Data

Table 2.3-1 Thyratron-Tube-Type Cycloconverter

Cycloconverter Rating (kva 0.7 pf)	5	50	500
Tube Ratings			
Average Current (amp)	1.67	16.7	167
Anode Voltage (volts)	500	500	500
Ionization time (microsec)	1	1	1
Deionization time (microsec)	100	100	100
Tube Power Dissipation (watts)			
Heater	15	50	500
Anode	17	170	1700
Grid	10	50	460
Total	42	270	2660
Physical Parameters of Tube			
Cathode Area (sq. cm.)	10	70	700
Diameter (inches)	4	5	10
Length (inches)	6	7	15
Weight (pounds)	1.5	4	40
Min. Anode Temp. (°C)	650	650	650
Max. Anode Temp. (°C)	850	850	850
Min. Grid Temp. (°C)	650	650	650
Max. Grid Temp. (°C)	750	750	750
Estimated Loss and Weight of Control, Inductors, Heater Transformer			
Loss (watts)	120	280	1200
Weight (pounds)	10	18	53
Temperature (°C)	80	80	80

B. Mechanical Design - Parametric evaluation of gas tube frequency changer cooling and packaging was based on this same approach used for thyristor designs as described in the Second Quarterly Report. As a result of the high operating temperature (1382°F avg.) and the size and weight of the gas tubes, this evaluation was based on the following assumptions.

- a. Liquid potassium is the coolant.
- b. Tantalum T-111 alloy is the cold plate material.
- c. Steel is the package material.
- d. Mechanical support structure is required in addition to adhesive bonding for gas tube mounting.
- e. Inductors, control components and heater transformers are grounded together and packaged separately from the gas tubes. These components require a low temperature (below 200°F) cooling system.

The results of this evaluation are presented in Figures 2.3-1 and 2.3-2. The weights shown in Figure 2.3-1 includes the packaged weight of the inductors, controls, and heater transformer. The coolant average temperatures and flow rates of Figure 2.3-2 are for the potassium system only. The small temperature drop from the gas tubes to the coolant result from the large base area through which the majority of the heat is conducted.

2.3.4 Plans for Coming Quarter

Effort in the coming quarter will be devoted to the analysis of the parametric data to permit the final selection of the conceptual frequency changer designs.

In addition, the final parametric data will be compiled for inclusion in the topical report for the power conditioning study.

Figure 2.3-2

Gas Tube Frequency Changer Parametric Data

2.4 Power Conditioning Study

2.4.1 Rectifiers

A. Summary of Past Quarter

1. Electrical Design - During this reporting period, the remaining parametric designs were completed for the silicon diode rectifier systems. The three-phase, full-wave bridge used for all of the previously reported rectifier systems was retained for the 500 and 1000 kilowatt, 30 kilovolt systems documented in this report. The results of the 120 volt d-c bus rectifier systems, which are also documented in this report, use a six-phase, single-way configuration (current flows in one direction in transformer secondary). The transformer for this rectifier system consists of one or two groups of two electrically isolated, wye-wound secondaries with an interphase transformer connected between their neutrals. This single-way rectifier circuit was selected because it offers the greatest advantages with regard to diode current loading, and with the exception of the three-phase, full-wave bridge, the transformer for this rectifier configuration has the highest utilization factor of any six-phase circuit. (Refer to Table III-2, Appendix B of the First Quarterly Technical Progress Report⁽¹⁾).

The design approach, design guidelines, and basic assumptions applied to the silicon diode rectifier systems reported in the First⁽¹⁾ and Second⁽²⁾ Quarterly Technical Progress Reports were retained. That is, the rectifier leg peak inverse voltage rating of 2.25 times the inverse voltage rating under normal system operation and a rectifier short-circuit current capability of 300 percent of normal rating for five seconds was used to determine the individual diode rating and the total quantity of diodes required in the rectifier assemblies. In addition, because the individual silicon diode voltage and current ratings presently available for the parametric designs of this study are not compatible with the system requirements, it is necessary to connect individual diodes in series and parallel. Where it has been necessary to use diodes in series, voltage division across the series diodes is accomplished by shunting each diode with a resistor-capacitor network. To provide the required current capacity, diodes used in parallel (which have been suitably derated) are matched with regard to their forward voltage and current characteristics as a function of temperature.

In addition to the silicon diode rectifier systems, parametric designs were initiated and completed, in this reporting period, on a total of seven gas and vapor tube diode rectifier systems.

2. Parametric Data, Silicon Diode Rectifiers - Tables 2.4-1 and 2.4-2 list the electrical component identity and list the calculated quantities of weight, power losses, and conversion efficiency for the 120 volt and the 30 kilovolt silicon diode d-c bus rectifier

Table 2.4-1 120 Volt DC Silicon Diode Rectifier Assembly System

DC Bus Power (kw)	25	75	250	500
AC System Freq. (Hz)	400-3200	400-3200	400-3200	400-3200
DC Bus Current (amps)	208	625	2083	4166
Rectifier Circuit	Six-Phase Single Way*	Six-Phase Parallel Single Way**	Six-Phase Parallel Single Way**	Six-Phase Parallel Single Way**
Qty. Rectifier Assemblies	1	1	1	1
Diode	JEDEC	JEDEC	JEDEC	JEDEC
Type	1N3294	1N4593	1N4053	1N4053
Rect. Total Current (amps)	208	625	2083	4170
Peak Amps/Rect. Leg	104	156.25	521	1043
Avg. Amps/Rect. Leg	34.7	52.1	173.7	347.5
PIV (volts)	800	800	700	700
Series Diodes/Rect. Leg	1	1	1	1
Parallel Diodes/Rect. Leg	None	None	2	4
Total Qty. Diodes	6	12	24	48
Total Losses (watts)	259	77	2330	4660
Total Weight (lbs)	0.938	1.88	12	24
Total Component Weight (lbs)	0.938	1.88	12	24
Total Conversion Eff. (%)	98.97	98.97	99.08	99.08

* The transformer or restifier power source connection is six-phase, double-
wye (two wye connected windings with interphase transformer).

** The transformer or rectifier power source connection is six-phase, parallel
double-wye (two groups of two wye connected windings with either one common
or two separate interphase transformers).

Table 2.4-2 30 Kilovolt DC Silicon Diode Rectifier Assembly System

<u>DC Bus Power (kw)</u>	500	1000
AC System Freq. (Hz)	400-3200	400-3200
DC Bus Current (amps)	16.7	33.3
Rectifier Circuit	Three-Phase	Full-Wave Bridge
Qty. Rectifier Assy	1	1
<u>Diode</u>	Westinghouse Type	Westinghouse Type
Type	404Z	402Z
Amps/3 Phase Bridge	16.7	33.3
Amps/Bridge Leg		
Peak Amps	16.7	33.3
Avg. Amps	5.57	11.1
PIV (kv)	1	1
Series Diodes/Rect.Leg	71	71
Parallel Diodes/Rect. Leg	None	None
Total Qty. Diodes	426	426
Total Losses (watts)	2300	4150
Total Weight (lbs)	6.66	16
<u>Resistor</u>	Dale Type	Dale Type
Type	RS-10-39	RS-10-39
Resistance (k-ohms)	250	200
Total Qty. Resistors	426	426
Total Losses (watts)	136	170
Total Weight (lbs)	8.52	8.52
<u>Capacitor</u>	Bendix Type	Bendix Type
Type	E-200	E-200
Capacitance (mfd)	0.01	0.01
Total Qty. Capacitors	426	426
Total Losses Max.(watts)	67.3	67.3
Total Weight (lbs)	8.1	8.1
Total Component Weight (lbs)	23.28	32.62
Total Losses Max. (watts)	2053.3	4387.3
Rectifier Conversion Eff.(%)	99.50	99.56

systems respectively. This completes the three-phase rectifier systems to be evaluated in the parametric study.

On the basis of the Power Uses and Mission Study it was concluded that the 20 volt rectifier systems would not be necessary since this voltage system would probably be intended for heater loads only. These loads can be supplied from the alternating current supply through a transformer. In addition, the 20 kilovolt rectifier parametric designs had been deleted since this information can be extrapolated from the 10 and 30 kilovolt systems.

3. Parametric Data, Gas and Vapor Tube Diode Rectifiers - Tables 2.4-3, -4, and -5 identify the components and list the calculated quantities of weight, size, power losses, and conversion efficiency for the 1, 5, and 30 kilovolt gas and vapor tube diode d-c rectifier systems respectively. The results are based on information obtained from the General Electric Company, Schenectady, New York. The diode tube preliminary designs used for this parametric study include safety factors for withstanding transient voltages of 2.25 times the normal system rating and short-circuit currents up to 300 percent for five seconds. In the event of extreme transient voltages or currents, where arc-back is induced, the tubes will survive and continue normal operation in succeeding cycles. These tubes have not been fabricated. The information in the tables, represents estimated tube characteristics based on existing high temperature tube technology as established on NASA development contracts NAS3-6005, NAS3-6469, NAS3-8525, and NAS3-9423 for gas and vapor filled thyratrons and rectifiers.

An advantage of the gas and vapor tube diodes for the kilovolt d-c bus rectifier systems is their individual high voltage capability. Because of this capability, a total of only 6 tubes, as shown in the tables, are used for each three-phase, full-wave bridge parametric design. Another advantage of the gas and vapor tube rectifier systems is their ability to operate at high temperatures. The anode temperature for the Hydrogen Gas tubes is a maximum of 600°C; while there is a maximum anode temperature capability of 850°C for the Xenon Gas and Thallium Vapor tubes.

Comparison of results between the gas and vapor tube rectifier systems and identically rated silicon diode rectifier systems is reserved for the final report. Information which remains to be included in the tabulation for the gas and vapor tube diode systems is transformer weight. The transformers will be necessary to provide the tube heater power requirements at the proper voltage level.

4. Mechanical Design - The rectifier weights (includes coolant) efficiencies, coolant average temperature and coolant flow rate versus kilowatt rating for the silicon diode rectifier systems completed during this reporting period are presented in Figures 2.4-1 through 2.4-4. This data, with the exception of the 120 volt d-c rectifier system efficiencies, follows the general trends established by the systems reported in the Second Quarterly Technical Progress Report. The efficiencies of the 120 volt systems show

Table 2.4-3 1000 Volt DC Gas and Vapor Tube Diode Rectifier Assembly System

DC Bus Power (kw)	25	500
AC System Freq. (Hz)	400-3200	400-3200
DC Bus Current (amps)	25	500
Rectifier Circuit	Three-Phase Full-Wave Bridge	Three-Phase Full-Wave Bridge
Qty. Rectifier Assemblies	1	1
Diode Type	Xenon Gas	Thallium Vapor
Amps/3 Phase Bridge	25	500
Amps/Bridge Leg		
Peak Amps	25	500
Avg. Amps	8.33	166.7
PIV (volts)	1000	1000
Series Diodes/Rest. Leg	None	None
Parallel Diodes/Rect. Leg	None	None
Total Qty. Diodes	6	6
Total Conduction Losses (watts)	500	10,000
Total Heater Losses (watts)	300	3,000
Tube Dimensions (inches)	Diam = 5 Lgth. = 6	Diam = 10 Lgth. = 15
Total Tube Weight (lbs)	9	240
Total Component Weight (lbs)	9	240
Total Losses (watts)	800	13,000
Rectifier Conversion Eff. (%)	96.9	97.47
<p>Note: The results of this rectifier system is based on information obtained from the General Electric Company, Schenectady, New York. These tubes have not been fabricated. The designs represent estimated tube characteristics only.</p>		

Table 2.4-4 5000 Volt DC Vapor Tube Diode Rectifier
Assembly System

DC Bus Power (kw)	25	500
AC System Freq. (Hz)	400-3200	400-3200
DC Bus Current (amps)	5	100
Rectifier Circuit	Three-Phase Full-Wave Bridge	Three-Phase Full-Wave Bridge
Qty. Rectifier Assemblies	1	1
<u>Diode</u>	Thallium	Thallium
Type	Vapor	Vapor
Amps/3Phase Bridge	5	100
Amps/Bridge Leg		
Peak Amps	5	100
Avg. Amps	1.67	33.3
PIV (volts)	5,000	5,000
Series Diode/Rect. Leg	None	None
Parallel Diodes/Rect. Leg	None	None
Total Qty. Diodes	6	6
Total Conduction Losses (watts)	100	1,998
Total Heater Losses (watts)	90	600
Tube Dimensions (inches)	Diam = 4 Length = 6	Diam = 6 Lgth. = 8
Total Tube Weight (lbs)	9	30
Total Component Weight (lbs)	9	30
Total Losses (watts)	190	2,598
Rectifier Conversion Eff. (%)	99.25	99.48
<p>Note: The results of this rectifier system is based on information obtained from the General Electric Company, Schenectady, New York. These tubes have not been fabricated. The designs represent estimated tube characteristics only.</p>		

Table 2.4-5 30,000 Volt Gas Tube Diode Rectifier Assembly
Rectifier

DC Bus Power (kw)	500	5,000	10,000
AC System Freq. (Hz)	400-3200	400-3200	400-3200
DC Bus Current (amps)	16.67	166.7	333.3
Rectifier Circuit	Three-Phase Full-Wave Bridge	Three-Phase Full-Wave Bridge	Three-Phase Full-Wave Bridge
Qty. Rectifier Assemblies	1	1	1
<u>Diode</u> Type	Hydrogen Gas	Hydrogen Gas	Hydrogen Gas
Amps/3 Phase Bridge	16.67	166.7	333.3
Amps/Bridge Leg			
Peak Amps	16.67	166.7	333.3
Avg. Amps	5.55	55.56	111.1
PIV (volts)	30,000	30,000	30,000
Series Diodes/Rect. Leg	None	None	None
Parallel Diodes/Rect. Leg	None	None	None
Total Qty. Diodes	6	6	6
Total Conduction Losses (watts)	1,000	10,000	60,000
Total Heater Losses (watts)	600	6,000	12,000
Tube Dimensions (inches)	Diam = 6 Lgth. = 10	Diam = 10 Lgth. = 15	Diam = 16 Lgth. = 20
Total Tube Weight (lbs)	60	240	600
Total Component Weight (lbs)	60	240	600
Total Losses (watts)	1600	16,000	72,000
Rectifier Conversion Eff. (%)	99.68	99.68	99.29
<p>Note: The results of this rectifier system is based on information obtained from the General Electric Company, Schenectady, New York. These tubes have not been fabricated. The designs represent estimated tube characteristics only.</p>

Figure 2.4-1

Rectifier Parametric Data

Figure 2. 4-2

Rectifier Parametric Data

Figure 2. 4-3

Rectifier Parametric Data

Figure 2. 4- 4

Rectifier Parametric Data

a reverse trend with respect to previous data; however, the efficiency decrease is a negligible 0.103 percent.

In addition to the silicon diode systems, seven gas tube rectifier systems were evaluated with the results presented in Table 2.4-6. Parametric evaluation of gas and vapor tube diode rectifier systems cooling and packaging was based on the same basic approach used for silicon diode designs as described in the Second Quarterly Technical Progress Report. Due to the high operating temperatures (932°F to 1382°F) and the size and weight of the gas tubes, this evaluation was based on the following assumptions.

- a. Liquid potassium is the coolant.
- b. Tantalum T-111 alloy is the cold plate material.
- c. Steel is the package material.
- d. Mechanical support structure is required in addition to adhesive bonding for gas tube mounting.

Table 2.4-6 Gas and Vapor Tube Diode Rectifier System Parametric Data

DC Voltage	1000		5000		30 000		
DC Power (kw)	25	500	25	500	500	5000	10 000
Total Assembly Wt. (lb)	76.41	448.63	62.3	113.33	167	477.11	1082.64
Coolant Avg. Temp. (°F)	1350	1324	1355	1346	895	863	805
Coolant Flow Rate (lb/min)	3.12	63.21	0.63	12.64	6.32	63.2	379.2

2.4.2 Transformers

A. Summary of Past Quarter

1. Electrical Mechanical Design- The basic transformer electrical and cooling design approaches selected during the first and second quarterly reporting periods have been retained. Transformer computer designs have been made using high temperature materials and liquid potassium at average coolant temperatures of 500°F, 800°F, and 1100°F. The selected transformer coolant temperatures are compatible with the other electrical system equipment.

The transformer configuration used to generate the parametric design data was the same as Figure 3.19 (page 93) of the First Quarter Progress Report⁽¹⁾. Starting with two cooling ducts in the coil assembly, a transformer design was calculated with a maximum coil and core temperature which was 30°F greater than the average coolant temperature. Additional designs were calculated by increasing the coil and core temperatures, initially in 20°F increments and then in 100°F increments above the average coolant temperature until the maximum safe operating temperatures of the materials were attained. The design calculations were continued for each of four frequencies (400, 800, 2000 and 3200 Hertz) at constant input and output conditions and a constant coolant temperature until the transformer efficiency was equal to or less than 92 percent. If the transformer efficiency lower limit was not attained with two cooling ducts in the coil assembly and the core and conductor materials at their maximum safe operating temperature, additional cooling ducts were added to the coil assembly.

The material maximum operating temperatures used for the parametric designs were the same as presented in Tables 2.4-5 and 2.4-6 (pages 138 and 139) of the Second Quarter Progress Report⁽²⁾ with the exception that the conductor material temperature for the 500°F coolant system was 1400°F. In addition, the material selections as presented in those tables were modified as follows:

- a. Boron Nitride was used as the potting compound instead of Westinghouse Type W-839 for the 500°F coolant system.
- b. Beryllia was used as the rigid insulation instead of 99 percent Alumina for the 1100°F coolant system.

2. Parametric Data - Approximately 95 percent of all the single and three-phase transformer designs specified in Table 3.4 (pages 87 through 90) of the First Quarterly Technical Progress Report⁽¹⁾ have been completed. Examples of the transformer parametric designs obtained are presented in Figures 2.4-5 through 2.4-15. A program for machine processing the remaining transformer data into curves will be used according to the requirements of Table 3.4.

Figure 2. 4-5

Three Phase Transformer Parametric Data

250 KVA, 500 VOLT IN, 428 VOLT OUT, 800°F COOLANT

Figure 2. 4-6

Three Phase Transformer Parametric Data

Figure 2. 4-7

Three Phase Transformer Parametric Data

10000 KVA, 1000 VOLT IN, 2140 VOLT OUT, 500°F COOLANT

Figure 2. 4-8

Three Phase Transformer Parametric Data

Figure 2. 4-9

Three Phase Transformer Parametric Data

Figure 2. 4-10

Single Phase Transformer Parametric Data

Figure 2.4-11

Single Phase Transformer Parametric Data

Figure 2. 4-12

Single Phase Transformer Parametric Data

Figure 2. 4-13

Single Phase Transformer Parametric Data

1000 KVA, 1000 VOLT IN, 11000 VOLT OUT, 800°F COOLANT

Figure 2. 4-14

Single Phase Transformer Parametric Data

Figure 2. 4-15

Single Phase Transformer Parametric Data

2.4.3 Plans for Coming Quarter

Effort in the coming quarter will be devoted to the analysis of parametric data to permit the final selection and design of the rectifiers and transformers for the conceptual system designs.

In addition, the parametric data, particularly for the power transformers, will be prepared in final form for the power conditioning topical report which will be completed in the next quarter.

3. SYSTEM DEFINITIONS

3.1 Nuclear Mechanical Systems

3.1.1 Summary of Past Quarter

In order to evaluate and optimize each of the various electrical system components relative to the others, at least one common design parameter must be chosen as a basis for comparison. For space power systems, the one most important parameter is weight, both the physical weight of the components and the weight penalty attached to its less than 100 percent efficient operation. This weight penalty consists of two parts, that of the power system supplying make-up power to account for the losses and that of the cooling system to reject the losses. This means that, in order to evaluate each electrical component individually for minimum weight, the specific weight* of all of the power supply system (and components therein) must be known as well as the specific weights of the heat rejection system and components.

A part of the present study has been to determine the approximate weights of the various powerplant components. This was accomplished by reviewing the work of past conceptual system design studies and either scaling the powerplant weights shown to coincide with the four ratings of the design study or calculating new weights based on new designs. Because of the lack of large rating (several megawatt) conceptual designs in the previous studies reviewed, considerable scaling and analyses had to be done on the 5 and 10 megawatt ratings.

The tabulation of the individual component weights has been completed and the weights which were determined are listed in Table 3.2-1 for the four basic ratings at 500, 800, and 1100°F temperature. Complete details of how the various weights were determined will be included in the final report. A few words of explanation are in order however.**

The auxiliary radiator cooling system does not show a separate pump. The pump to circulate the auxiliary coolant flow is an integral part of the primary radiator (NaK) pump. The secondary radiator system contains MIPB fluid and operates at an average temperature of 175°F, not the 500 to 1100°F implied by the table; they are listed as such to show their relationship with the various electrical ratings irrespective of the 500 to 1100°F coolant temperatures. The radiator weights are based on estimated losses as determined by this study, the Power Uses and Missions study and

* Usually specified in a convenient form as pounds per kilowatt of power supplied or pounds per kilowatt of heat rejected.

** Nomenclature is the same as specified in Reference 2, Section 3.2.2.

Table 3.1-1 Powerplant Component Weights

Component	Rating Temp. °F	0.35 MW _e			1.0 MW _e			5.0 MW _e			10.0 MW _e		
		500	800	1100	500	800	1100	500	800	1100	500	800	1100
1. Reactor - 10,000 hr. life 40,000 hr. life	Units lbs lbs	← 1300 → ← 1618 →			← 3390 → ← 4370 →			← 5460 → ← 21700 →			← 10890 → ← 43600 →		
2. Boiler	lbs	← 97 →			← 277 →			← 1385 →			← 2770 →		
3. Condenser	lbs	← 63 →			← 180 →			← 901 →			← 1802 →		
4. Reactor Motor Heat Exchanger	lbs	Assumed to be an integral part of the motor											
5. Boiler Feed Pump	lbs	← 29 →			← 48 →			← 125 →			← 217 →		
6. Primary Radiator Pump	lbs	22 25 23			38 41 40			144 152 154			290 286 284		
7. Reactor Coolant Pump	lbs	← 15 →			← 21 →			← 86 →			← 160 →		
8. Primary Radiator	lbs	← 1500 →			← 4291 →			← 21450 →			← 42910 →		
9. Turbine	lbs	27 36 49			130 156 260			1576 1576 2740			2664 4000 5330		
10. Misc Powerplant	lbs	← 53 →			← 151 →			← 756 →			← 1512 →		
11. Misc Power Conversion System	lbs	← 93 →			← 236 →			← 1013 →			← 1853 →		
12. Subtotal - 10,000 hr. 40,000 hr.	lbs	3189 3507	3201 3519	3212 3530	8736 9716	8765 9745	8868 9848	32880 49120	32888 49128	34054 50294	65068 97778	66400 99110	67728 100438
13. Generator	lbs	294	332	490	1008	1151	1749	5094	5318	10644	9769	14064	25977
14. Specific Weight (S _e)-10,000 hr. 40,000 hr.	lb/kwe lb/kwe	9.97 10.86	10.09 11.00	10.59 11.49	9.74 10.72	9.92 10.90	10.62 11.60	7.60 10.84	7.64 10.89	8.94 12.18	7.48 10.18	7.62 11.32	9.37 12.64
15. Auxiliary Radiator and Heat Exchanger	lbs	605	207	87	1420	480	207	6200	2100	896	12640	4280	1560
16. Specific Weight (S _L)	lb/kw	11.8	4.0	1.7	11.8	4.0	1.7	11.8	4.0	1.7	11.8	4.0	1.7
17. Secondary Radiator	lbs	← 378 →			← 953 →			← 6600 →			← 12600 →		
18. Secondary Coolant Pump	lbs	← 13 →			← 16 →			← 34 →			← 46 →		
19. Specific Weight (S _{L'})	lb/kw	← 44 →			← 44 →			← 51 →			← 51 →		
20. Shield - 10,000 hr. unmanned 40,000 hr. unmanned 40,000 hr. unmanned manned	lbs lbs lbs lbs	← 688 → ← 5350 → ← 1021 → ← 5690 →			← 1560 → ← 8760 → ← 2436 → ← 9710 →			← 2912 → ← 13400 → ← 12860 → ← 35600 →			← 5790 → ← 2250 → ← 25240 → ← 61000 →		
21. Total System - 10,000 hr. unmanned manned 40,000 hr. unmanned manned	lbs lb/kwe lbs lb/kwe lbs lb/kwe lbs lb/kwe	5173 14.8 9835 28.0 5818 16.6 10487 30.0	4819 13.7 9481 27.0 5470 15.6 10139 29.0	4868 13.9 9530 28.2 5519 15.8 10188 29.1	13693 13.7 20893 20.9 15549 15.6 22823 22.8	12925 12.9 20125 20.1 14781 14.8 22053 22.1	13353 13.4 20553 20.6 15209 15.2 22443 22.4	53720 10.7 64208 12.8 79908 16.0 111648 22.3	49852 11.1 60340 12.1 76040 15.2 98780 19.8	55340 10.0 65628 13.1 81328 16.2 104068 20.8	105913 10.6 122623 12.3 152368 15.2 188128 18.8	98885 9.9 115595 11.6 155340 15.5 191100 19.1	113701 11.4 130411 13.0 165861 16.6 201621 20.2

the Motor and Generator Parametric Screening studies. Also, the component weights are being listed as if for a single system without redundancy; parallel systems are being analyzed as part of the Electrical Systems Definition Task.

The turbine and generator weights are based on design speeds according to the optimum generator speeds listed in Section 2.1.2.A.2. In selecting the speeds, it was assumed that turbines could operate at the selected values.

The shield weights are based on the following parameters:

- manned - 1.5 mrem/hour
 - 60 ft. diameter dose plane
 - 150 ft. separation distance
- unmanned - 3×10^{12} nvt (combined equivalent dose)
 - 25 ft. diameter dose plane
 - 50 ft. separation distance

To adjust the shield weights for other separation distances, the weights must be multiplied by the correction factors given on Figures 3.1-1 and 3.1-2.

The specific weights for the turbine shaft power (S_g in Reference 2) are not summarized in the Table 3.1-1, they are presented in Figure 3.1-3. Examination of the data reveals that the specific weight at 40,000 hours is approximately 1.1 to 1.5 times that at 10,000 hours. Likewise, the specific weight of the total system, as summarized in the following, is heavier at 40,000 hours.

Table 3.1-2 Average Ratio of Total System Specific Weights at 40,000 and 10,000 hours

KW rating	350	1000	5000	10,000
Manned	1.06	1.10	1.69	1.60
Unmanned	1.14	1.15	1.40	1.39

Notice that, as the coolant temperature increases from 500 to 800 to 1100°F for the various ratings, the auxiliary or coolant radiator and heat exchanger weight decreases an amount less than the turbine and generator weight increase. The net result is that the lightest systems - least specific weight - occur at the 800°F electrical system coolant condition rather than at 1100°F. This is indicative of the loss in electrical performance per pound of electrical system that usually occurs at the higher temperatures.

Figure 3.1-1

Manned Vehicle Shield Weights

Figure 3.1-2

Unmanned Vehicle Shield Weights

Figure 3.1-3
Turbine Shaft Power Specific Weight

3.1.2 Plans for Coming Quarter

Task is complete except for final documentation into Final Report.

3.2 Electrical System Definition

3.2.1 Summary of Past Quarter

Figures 3.2-1 through 3.2-5 show a general system configuration for each of four conceptual missions. These missions are based on data generated in the previous mission studies. Note that these systems consist basically of one each of the required power generation and power conditioning equipment. Generally this approach will lead to lighter total system weight. For long duration missions requiring multi-megawatt electrical power systems, a configuration of several lower rated systems, whose total capacity equals or exceeds the required mission power requirements is suggested. The primary reason for this is to make further assurance of mission success if not to avert total disaster. Should some vital part of a single power system fail, the space vehicle would be completely lost. However, with a system consisting of multiple power generating systems, a single failure would not result in complete loss of functions. Hence mission reliability can be increased by furnishing a power system with several power sources.

A second advantage of this approach is the building block ability since larger rated systems can be constructed by simply adding additional power modules to a basic electric power system.

From Figures 3.2-1 through 3.2-4, it is noted that the primary loads (propulsion) are generally made up of many submodules. Hence, it would be unrealistic to make a single power conditioning system for all the engines. The better approach is to modularize the engines and furnish each with a separate power conditioning system including the necessary control and protection to assure proper engine start and survival during an engine fault. This approach may not prove too practical from the standpoint that the single engine rating will be at most several kilowatts while the mission will require one or more megawatts of engine capacity. This situation means that the multiplicity of power conditioning equipment may become quite large. A compromise can be made which will assure balanced thrust vectors, minimize power transients, and still provide improved engines system reliability. This is accomplished by choosing a number of engines which will supply a balanced thrust vector and connecting them to a single set of power conditioning equipments as shown in Figure 3.2-1. For the ion-propulsion engines, as many as seven different power conditioning

Figure 3.2-1

Preliminary Concept No. 1 for Unmanned Scientific Probe

Figure 3.2-2
Preliminary Concept No. 1 for Manned Interplanetary Mission

Figure 3.2-5
Preliminary Concept for Lunar Base

Example Shown: $x = 25\text{KW}$

Figure 3.2-3
Electric Engine Module (1 of n)

Figure 3.2-4
Preliminary Concept No. 1 Synchronous Orbit Space Station

units per engine are required. During certain engine fault conditions, three of these supplies must be shut down while the others should remain operating. The arrangement for this concept is shown in Figure 3.2-3. The bulk of the required engine power is conditioned in the three rectifier units. Note that one rectifier does not require a transformer. This is accomplished by rating the generator at an alternating voltage to achieve the required 3000 volts, d-c power. Since this portion of the engine represents 75 percent of operating load, a weight savings results. Because the rectifier bridge is a three-phase full-wave type, the neutral of the generator cannot be connected to the common electrical connection of the engine. This does not result in a serious drawback, however, because the rectifier forms a balanced three-phase load and all other system loads will be isolated by a transformer. Hence, all system loads and the engine can have a common connection.

If the basic single electric-power system concept is dropped in favor of multiple electric-power system concept, many other configurations can be realized. These configurations fall into one of the three following categories as depicted in Figure 3.2-6:

1. electrically isolated system load buses,
2. electrically isolated system load buses with provisions for interconnections, and
3. paralleled system load buses

Parallel systems are potentially more flexible because no restriction on the rating of a load is imposed. Other benefits are the increased fault clearing capacity and non-interruption of power as generation systems or loads are added to or removed from the parallel system. The most severe drawback to this approach, however, is the desire not to have a throttle control for the turbine, since the turbine speed must be controlled in order to properly share load among the paralleled generators. Other considerations, though not serious, are the more complex control and protection circuits for locating faults and forcing real and reactive load sharing. In some types of electric-power systems, adequate parallel operation can be achieved by depending on prime movers with a soft speed load characteristic. With systems of this type, full utilization of power potential cannot be realized and further the system frequency will vary several percent as the system loads vary. The system utilizing this particular approach to parallel operation would have to be matched to this requirement.

Another approach to parallel system operation is to utilize the fact that the bulk of systems loads are direct-current loads. Since parallel d-c systems do not require speed control to assure load sharing the need for turbine speed control is removed and artificial droop can be designed into the generator excitation system to assure proper load sharing.

The approach would be to parallel the a-c generators through the rectifiers, sense load current differences and alter load

Figure 3.2-6

Multiple Power Source Concept of Achieving a Specific Rating

division by controlling generator excitation with voltage magnitude and load current difference feed back signals. For this approach to work, the d-c load used in the paralleling feed back loop should be in the range of 75 to 80 percent of the total load on each generator. Further a protective function should be included to assure that the paralleled d-c load and the sum of other generator loads do not exceed the capacity of any one generator system. If the generating systems are quite stiff, the actual voltage change will be quite small thus not affecting the non-paralleled loads and further speed control can be maintained by means of parasitic-load speed controllers. Because the bulk of the loads must be direct current and must represent the major portion of system capacity, this approach will not be applicable to all missions. For example the major d-c loads in Figures 3.2-1 and 3.2-2 are electric engines, but the loads are split into several smaller rated power conditioning equipments to prevent large load changes resulting from such fault conditions as engine arc over.

Obviously, if each group of electric engines is to operate isolated from other engines, the engine group cannot have paralleled power conditioning equipments. The systems defined for this mission would therefore be more adaptable to an isolated arrangement of power systems unless the power systems are paralleled at the load side of the control contactor (a-c side of all loads).

From the above and analysis of various types of loads for the conceptual missions, the isolated type of multiple power-generating systems appears to be the best choice. To enhance reliability, a means of multiple load connection points and provisions for connecting a single load to more than one power source is desirable. The system configurations for multiple power systems therefore falls within category two of the various types of system interconnections.

3.2.2 Plans for Coming Quarter

Isolated power generation systems with load-bus interconnection provisions will be the selected approach for all systems whose individual loads are less than 50 percent of a single generator rating. The various loads will be connected to load buses arranged to balance the load among the several generators. For loads requiring more than the capacity of a single generator, parallel operation must be considered. While this situation is not foreseen for these conceptual missions, future requirements, such as advanced Lunar Bases where multi-megawatts may be required, may justify the benefits of paralleled power systems and may warrant the increased complexity in the turbine speed control loop. The power network would be similar to present day terrestrial systems.

Figure 3.2-7 shows an arrangement of multiple generation systems for isolated operation.

GC - Generator Contactor
TC - Transfer Contactor

Figure 3.2-7

Single Line Diagram of Isolated-Load Bus System

Because the various conceptual missions cover a wide range of power ratings, the approach to conceptual equipment design will be accomplished by choosing various equipments from Figures 3.2-1, 3.2-2, 3.2-4, and 3.2-5. A larger-rated system can be established by taking a multiplicity of the smaller-rated systems. At this point, possible ratings for conceptual equipment design include:

Generator: 350 kva, 1 mva, 2 mva and 10 mva
Frequency Changer: 20 kva, 50 kva, 100 kva, 120/208 volt
and 100 kva, 220/416 volt
Motors: 280 HP - 220/416 volt and 4, 10 & 40 HP - 120/208 volt
TR Units: To be selected.

4. EXPERIMENTAL VERIFICATION

4.1 Magnetic No-Load Loss Tests

4.1.1 Summary of Past Quarter

All stator components were completed. The endbells were mounted to the stator and bearing housing diameters were finish machined to achieve excellent bearing alignment. These diameters were indicated with a precision dial indicator (0.0001 inch/division) and found to be concentric within 0.0001 inch.

The rotor was machined to blend all sharp corners. Eight rotor poles were slotted 0.100 inch deep at the pole faces (See Figures 4.1-1 and 4.1-2). One of these poles was slotted with 0.004 inch thick abrasive wheels but because of frequent wheel breakage, 0.006 inch thick wheels were substituted on the remaining poles. The slotting of seven pole faces was completed using a single set of abrasive wheels with no wheel breakage. At this point in the manufacture of the rotor, it was removed from the slicing machine (Doall Slicer) for a period of approximately two weeks to permit inspection for cracks both ultrasonically and by magnetic particle.

Figure 4.1-3 illustrates the rotor emmersed in a water tank and the transducer in scanning position during the ultrasonic testing.

The rotor was then reinstalled on the slicing machine in a manner identical to the previous installation. A new set (96) of aluminum oxide abrasive wheels was used. A test piece was clamped to one of the rotor poles in a manner similar to that previously employed to pre-test the wheels. At only 0.004 inch depth-of-cut a sharp momentary vibration was heard and breakage of approximately 10 of the outboard wheels occurred. Minor adjustments were made but did not correct the breakage problem. The spindle drive motor-pulley combination was dynamically balanced and the gibs were tightened on the machine ways to reduce any possible looseness, but this did not correct the problem. Further investigation suggested the new wheels were dull and were loading the spindle drive motor beyond rating. The old 0.006 inch thick abrasive wheels were again placed on the arbor and both a sample piece and a complete rotor pole were slotted with these wheels with no difficulty.

The associated test equipment including the test chamber drive coupling, and feedthrough parts were approximately 90 percent completed.

4.1.2 Plans for Coming Quarter

The No-Load Loss Test Assembly and testing will be completed. Evaluation of the test data and preparation of the test report will be completed.

Figure 4.1-1

Rotor Pole Face Slotting Operation

Figure 4.1-2
Slotted Rotor Pole Faces

Figure 4.1-3

Ultrasonic Inspection of Rotor

4.2 Rotor Cooling Concepts

4.2.1 Summary of Past Quarter

A test fixture with the rotor assembly that contains radial coolant passages was assembled and tests were initiated on February 13, 1967. The primary objective of the experiment was to verify the flow capacity and stability of a rotor cooling concept which has cooling passages that diverts the flow radially outward and then inward. The initial tests were terminated on the third startup of the fixture. During the startup, the rotor speed reached approximately 4000 rpm at which point it began to slow down. The fixture stopped with a locked rotor. A teardown and inspection of the parts revealed that the bearing on the anti-drive end of the rotor had failed. High wear of both the journal and the pads occurred in the circumferential direction under the central portion of the pads. It was concluded at this time that the failure was due to self-loading caused by debris most likely produced by scoring and tracking before the bearing had a chance to establish the proper film within the clearance. A failure of this type can also be caused by an inadequate clearance or loss of clearance within the bearing due to thermal expansion of the components. It was apparent that a change in the bearing design would have to be made. The bearings were changed by: (a) replacement of the stainless steel, type 416, bearing journals with tungsten carbide, (b) replacement of pads with a tool steel heat treated to a hardness of RC 63, and (c) increasing the diametrical clearance from $0.0030 + 0.0002$ to $0.0040 + 0.0002$ inches. These changes were completed on 4.14.67 and the tests were restarted. Rotor flow calibrations were performed at 24,000, 20,000, and 16,000 rpm without incident or indication of any flow problem.

The test results show that the only requirement of the external fluid supply system (for the rotor) was to deliver the desired flow to the central part in the antidrive end of the rotor. The rotor pumps the fluid through the rotor at all speeds. In addition, the flow was stable and was not affected by the speed of the rotor or the back-pressure on the flow circuit. A final report on the experimental and other effort expended upon the rotor cooling concept with radial passages is being prepared. This report includes not only the experimental verification results, but will also include notes on: (a) secondary flows in a rotating pipe, (b) friction factor for flow in a rotating pipe based upon the analogous case of flow in a curved pipe, (3) centrifugation of heavy materials in rotor passages, and (4) pressure head developed in a rotating system due to centrifugal force and density gradient.

4.2.2 Plans for Coming Quarter

Complete final report write-up.

REFERENCES

1. Design Study, Electrical Component Technology for 0.25 to 10.0 Megawatt Space Power System, First Quarterly Report, AEC Contract AT(04-3)-679, Westinghouse Electric Corp., Aerospace Electrical Division, AED R&D Report SAN-679-1, November 30, 1966.
2. Design Study, Electrical Component Technology for 0.25 to 10.0 Megawatt Space Power Systems, Second Quarterly Report, AEC Contract AT(04-3)-679, Westinghouse Electric Corp., Aerospace Electrical Division, AED R&D Report SAN-679-2, February 28, 1967.
3. Electrical Engineer's Handbook, Pender & Del Mar, 4th Ed., John Wiley & Son, pp. 11-19,

APPENDIXES

APPENDIX A

GENERATOR AND MOTOR STATOR BORE-SEALS AND ROTOR CANS

Generator and motor windings fabricated from present state-of-the-art materials must be protected from attack by alkali-metal coolants if their metal vapors are present in the rotor cavity. Rotors with windings may be protected in metal cans.

Protection of the stator from potassium vapor requires a bore-seal in the form of a thin-wall tube in the radial gap of the alternator. A thin-wall ceramic tube has been judged best suited to provide a good combination of resistance to attack by alkali metal and electric resistivity high enough to limit eddy-current losses to low values. The ceramic tube in the gap between the stator and rotor poles must be bonded to metal end members for sealing to the alternator frame in order to provide a sealed stator enclosure. In the event that both the stator and rotor would be vented to space, the seal would not necessarily be hermetic.

A. Background

Several programs have been carried on for development of fabrication techniques to provide alkali-metal resistant bore-seals and cans. Developments under the programs referenced below are discussed in the next section on Program Developments.

1. Air Force Program - An Air Force program for development of a 467 KVA potassium cooled SNAP-50/SPUR type generator included a task for development of a stator bore-seal in that unit. Technical Report ASD-TDR-63-677, Part I (1963) and Part II (1967), covers this work carried out on SNAP-50/SPUR Development Contracts AF33(616)7379 and 8322, AF33(657)8954, and 10922, AF33(615)1551 and 2326.
2. NASA Program - A NASA sponsored program was carried out for study of ceramic-metal seal technology appropriate for fabrication of stator bore-seals for service at higher temperatures up to 1600°F. Research and Development Program on Magnetic, Electrical Conductor, Electrical Insulation and Bore Seal Materials, Contract NAS 3-4162. Technical Report NASA-CR-54093 (1964) covers much of the past work done under this study.

3. CANEL Program - An AEC sponsored program for development of liquid-metal pump motors in the CANEL space power system included application of motor stator bore-seals and metallic enclosure cans for the rotor.

B. Program Developments

1. Bore-Seals to 1000°F - Alumina is a widely used ceramic in commercial applications involving its being brazed to metal components in vacuum tight joints. Superior strength and better availability in special shapes were added factors which made alumina an initial first choice over beryllia for stator bore-seals to operate below 1000°F in the investigations carried on under the Air Force program for development of the SNAP 50/SPUR type generator.

Brazing trials were performed with the three types of specimens shown in Figure A-1. Type CLM-15 tensile specimens from ceramic bodies of five different alumina of high purity were used in brazing to thin (0.015 inch) metal washers of refractory and non-refractory alloys. Five different commercial brazing alloys were used in early trials by conventional processes. Further brazing was done with titanium and zirconium base alloys of the "active-metal" type produced in twelve special melts from high purity materials. The brazing trials and subsequent tensile testing and 10,000-hour exposure to potassium vapor at 900°F demonstrated alumina of 99.8 percent purity brazed under high-vacuum at about 1850°F with the "active-metal" alloy of 75Zr/19Cb/6Be to metal members of 99Cb/1Zr alloy produced the best combination of high tensile strength (7500 psi), vacuum tightness, and good brazing characteristics of those specimens which resisted potassium attack.

Exposure tests with 2.5 inch diameter tubular specimens having a uniform 0.375-inch thick wall demonstrated the materials were resistant to both potassium liquid attack (on the bottom brazement) and to vapor (on the top) at 1100°F over a 1000-hour period.

The 11.5 inch diameter brazement specimen shown at the bottom of Figure A-1 also had a uniform 0.375 inch wall thickness because that is the dimension chosen for the thicker brazed section at the ends of thin-wall tubes. Thin-Wall (0.090 inch) tubes, as shown in Figure A-2, were produced also from CE998 alumina by WESGO. Brazing trials with the large tubular bore-seal type specimens revealed that titanium base brazing alloys did not produce vacuum tight joints in these heavier assemblies which had relatively slow heating and cooling ratios. However, the zirconium base alloy containing beryllium

Type CLM-15 1.5X

2.5" Dia. Tubular 0.5X

11.5" Dia. Tubular

Figure A-1

Types of Brazed Specimens in SNAP 50/SPUR Program

Figure A-2
Set of Thin-Wall (0.090-inch) Ceramic Components
For Prototype SNAP-50/SPUR Generator's Stator
Bore-Seal Assembly

did produce vacuum tight joints. Metal members of Cb-1Zr were 0.030 inch thick in these specimens because stress analyses indicated a need for that thickness.

Although most of the work carried out on the SNAP 50/SPUR generator bore-seal was of a materials development nature, extensive analytical work was done to determine and minimize the stresses in the bore seal, joint, and metal end-member. The work consisted of a computerized study of several 2-dimensional shell configurations (over fifty) subjected to all possible modes of steady state and transient conditions that the bore seal would see during fabrication, assembly and operation. As a result of this study, several configurations and design approaches were identified which would minimize stress in the bore seal and end members, thereby increasing its dependability.

2. Bore-Seals for 1000°F - 1600°F - At temperatures over 1000°F in longtime exposure to alkali-metal vapors, testing has demonstrated that alumina must be replaced by high-purity beryllia ceramics to withstand attack.

High-purity beryllia has not been available in the larger diameter tubes (over 6 inches diameter) for use as bore-seals. However, supplier capabilities have been improving in regard to fabrication of thin wall tubes of uniform high density from this ceramic.

The alloy of 60Zr/25Va/15Cb displayed the best combination of potassium resistance, strength, and good brazing characteristics from more than ten "active-metal" alloys evaluated in small modulus-bar brazed specimens. Specimens with Cb-1Zr alloy members brazed to beryllia ceramic with molybdenum surface metallizing had a strength of 25,000 psi both at 1600°F and room temperature. Their strength did not deteriorate after 500 hour exposure to potassium at 1600°F. Vapor exposure at that temperature for 2000 hours reduced the strength about 10 percent and liquid potassium caused the joint strength tests to vary inconsistently after exposure.

A test presently in progress on a 4 inch diameter bore-seal assembly of those materials at 1300°F has shown no evidence of potassium leakage after 5000 hours.

The tantalum base alloy, T-111 with 90Ta/8W/2Hf may be more compatible with assemblies now considered for future liquid-metal cooling systems from the standpoint of minimizing mass transfer. It has been found to wet well by brazing alloys in limited trials of about a dozen specimens.

Figure A-3

Thermal Expansion of Ceramic and Metal Bore-Seal Components
(from NASA-CR-54093)

The expansion curves in Figure A-3 show this alloy to be slightly better than Cb-lZr in matching alumina and beryllia. In high temperature tensile tests it has shown yield strengths of 110,000 psi at 1000°F and 80,000 at 1600°F; both are roughly three times those for the columbium base alloy.

3. Rotor Cans - A high speed motor's wound rotor needs an enclosing can for protection of its windings from alkali metal. The good mechanical properties of T-111 alloy at high temperatures and its resistance to alkali metal attack led to the choice of this material for the rotor can on CANEL pump motors. Metallic rotor cladding contributes some motor torque, but the electric resistivity of T-111 (43×10^{-6} ohm-cm at 900°F) is low enough to cause appreciable eddy current loss. The advantage of T-111's high strength is also partly overcome by its high density of 0.60 lb/in³.

APPENDIX B

CALCULATION OF THYRISTOR LOSSES IN A CYCLOCONVERTER CIRCUIT

Losses in the thyristor are usually determined from manufacturers data sheets based on the average current and the current waveform. This method does not account for switching losses, however, which may become significant at higher frequencies.

The loss calculations outlined herein require knowledge of the construction of the thyristor so that its resistance may be determined as a function of time. Expressions for instantaneous current are developed and used to determine the energy loss during an output cycle. The calculations herein are limited to a cycloconverter operating in a half-wave mode from a three-phase infinite bus source; the load is inductive and switching control is independent of the load.

A. Thyristor Currents

The load current is made up of a series of current pulses, each being conducted by one of the thyristors in sequence. Each current pulse consists of commutation current followed by conduction to the load. The voltage behind the current pulse is a sine wave triggered on at a varying phase angle.

When a thyristor is first turned on, assume that its resistance can be neglected in calculating the current through it. From rectifier commutation theory (reference 3) the current can be expressed as:

$$i = I_{cm} [\cos \alpha - \cos (w_s t + \alpha + \mu)],$$

from $w_s t = -\mu$ to $w_s t = 0$, (see Figure B-1)

$$\text{where } I_{cm} = \sqrt{3} E_m / (2 X_c),$$

E_m = Source voltage peak value,

X_c = commutating reactance,

α = firing angle,

w_s = angular velocity of source voltage,

μ = commutation angle which is

$$\mu = \cos^{-1} \left(\cos \alpha - \frac{I_c X_c}{E_m \sin \pi/3} \right) - \alpha$$

Figure B-1

Commutation in Rectifier Circuit When Operating with Phase Control

where I_c = current flowing in X_c at the beginning of commutation.

At the completion of commutation, the voltage behind the load current is

$$e_L = E_m \sin (\omega_s t + \gamma),$$

$$\text{where } \gamma = \alpha + \mu + \pi/6.$$

The load current may be expressed as

$$i = \left\{ \left[\sin(\theta - \gamma) + \frac{I_c Z}{E_m} \right] \exp^{-\omega_s t / \tan \theta} + \sin (\omega_s t + \gamma - \theta) E_m / Z, \right.$$

since the circuit impedance, Z , is inductive,

$$\text{where } \theta = \cos^{-1} (R/Z),$$

and R is the load resistance.

B. Thyristor Firing and Conduction Angles

The control of the cycloconverter is such that, as the controlling reference voltage increases positively, the positive thyristor bank switching control provides switching signals at the rate of three times the sum of the source and output frequencies. When the reference changes negatively the switching rate is three times the difference of the source and output frequencies. Thus the conduction angles may be defined as:

$$\omega_s T_a = \frac{\omega_s}{3(f_s + f_o)} = \frac{2\pi k}{3(k+1)}$$

$$\omega T_b = \frac{\omega_s}{3(f_s - f_o)} = \frac{2\pi k}{3(k-1)}$$

where k is the ratio of source frequency to output frequency, f_s/f_o .

To simplify the computation, assume that one of the source phase voltages reaches its maximum at the same instant as does the reference voltage. In Figure B-2, consider the number of switching points in the interval $(\pi/2 - \theta_o)$ during which the fundamental component of load current is positive and the reference voltage is rising. The last switching point in this interval occurs $\omega_s T_a/2$ radians before the end of the interval. The number of complete conduction periods in the interval is:

$$\begin{aligned} n_a &= K (\pi/2 - \theta_o) / (\omega_s T_a), \\ &= 3 (\pi/2 - \theta_o) (k+1) / 2\pi. \end{aligned}$$

Figure B-2

Cycloconverter Output Voltage Showing Phase Delay In Switching

The number of switching points in the interval, $(\pi/2 - \theta_0)$, is the largest integer less than $(N_a + 1/2)$, or

$$n_f = (n_a + 1/2) \text{ rounded to next lower integer.}$$

The number of conduction periods following the maximum point of the reference voltage while the fundamental component of load current is still positive is

$$\begin{aligned} n_b &= k(\pi/2 + \theta_0)/(w_s T_b), \\ &= 3(\pi/2 + \theta_0)(k-1)/2\pi. \end{aligned}$$

The switching points may be assigned numbers starting with the integer, N_f , as the first in the series and decreasing in steps of one

$$n = (n_f, (n_f-1), \dots, 1, 0, -1, \dots, n_e).$$

where

$$n_e = (n_f - n_a - n_b) \text{ rounded to nearest lower integer.}$$

The firing angle for any conduction period may be specified as:

$$\alpha_n = \left| \frac{(2n-1) \pi/3}{k + \frac{2n-1}{|(2n-1)|}} \right| \text{ radians.}$$

The value of α_n is always positive since it is a delay angle. Also, the denominator of the equation can have values of either $(k+1)$ or $(k-1)$ depending on the value of N .

The conduction angle for each current pulse may be stated for the period following the N th switching point as:

$$w_s T_n = \left[\frac{2n-1}{k + \frac{2n-1}{|(2n-1)|}} - \frac{2n-3}{k + \frac{2n-3}{|(2n-3)|}} \right] \frac{\pi k}{3}$$

C. Thyristor Turn-On Voltage

When a gating signal is given to the thyristor, it does not turn on instantaneously. Rather, the conducting area radiates from the gate at an approximately constant linear rate of speed. The conducting area is, thus, a function of elapsed time following application of the gating signal. The configuration of the thyristors considered in this study consists of a circular semiconductor crystal with a circular gate located at the center of the crystal. The area of the crystal is:

$$A_{RF} = (D^2c - D^2g)\pi/4$$

Where D_c is the crystal diameter

and D_g is the gate diameter.

During turn-on, the crystal area in conduction varies with time as

$$A = (S^2t^2 + StD_g)\pi$$

where S = rate of spread of conduction.

and t = elapsed time.

Since the time reference chosen is such that time is zero at the completion of commutation, the area equation must be modified so that conduction area is zero at the beginning of commutation.

Thus,

$$A_{RT}^1 = [S^2(t + \mu/w_s)^2 + S(t + \mu/w_s)D_g]\pi$$

The portion of the crystal which is conducting at any time is:

$$A_R = \frac{A_{RT}^1}{A_{RF}} = \frac{4[(w_st + \mu)^2 S^2/w_s^2 + (w_st + \mu)S D_g/w_s]}{D^2c - D^2g}$$

However, $0 < A_R < 1$

and the expression for A_R is valid from $w_st = -\mu$ to $wt = [(D_c - D_g)w_s/(2S)] - \mu$.

Data sheets for thyristors provide curves showing voltage drop as a function of instantaneous current for thyristors in full conduction. These curves may be approximated by an equation of the form

$$v = ai^b + c$$

where a , b , and c are constants required to fit the curve. (See Table B.1). During the turn-on period only a fraction, A_R , of the crystal is in the conducting state. The voltage drop, therefore, depends on the current per unit conducting area, rather than on current alone. A modification in the voltage equation is thus, necessary to describe the voltage drop during the turn-on period and may be expressed as

$$v_{to} = a(i/A_R)^b + c.$$

Table B.1 Thyristor Constants used in Dynamic Computations

Westinghouse Type	Gate Diam mm.	Crystal Diam mm.	Spread Rate mm/sec	Volt-Ampere Characteristics Equation Constants		
	Dg	Dc	S	a	b	c
218Z	3.0 *	18.7	10 ⁵	0.0284	0.585	0.9
219Z	1.5	11.5	10 ⁵	0.111	0.50	1.2
254Z	1.5	11.5	10 ⁵	0.158	0.408	0.6

D. Loss Calculations

Now the energy loss for each current pulse may be computed by summing the instantaneous power loss during each pulse.

$$W_n = \int_{-\mu_n/w}^0 (V_i)_{cn} dt + \int_0^{t_{1n}} (V_i)_{tn} dt + \int_{t_{1n}}^{t_{2n}} (V_i)_n dt$$

where the first turn occurs during commutation, the second during final spread of conducting area of the thyristor and the third during the rest of the conduction period.

$$(V_i)_{cn} = [a(i_{cn}/A_R)^b + c] i_{cn},$$

$$(V_i)_{tn} = [a(i_n/A_R)^b + c] i_n,$$

$$(V_i)_n = [a(i_n)^b + c] i_n,$$

$$i_{cn} = [\cos \alpha_n - \cos (w_s t + \alpha_n + \mu_n)] \sqrt{3} E_m / (2 X_c),$$

$$i_n = \{ [\sin(\theta_s - \gamma_n) + I_{(n+1)} Z / E_m] \exp^{-w_s t / \tan \theta} + \sin (w_s t + \gamma_n - \theta_s) \} E_m / Z$$

Since i_n flows through a rectifier it can have only positive values. If computation is negative, i_n is set to zero.

$$u_n = \cos^{-1} \left[\cos \alpha_n - \frac{I_{(n+1)} X_c}{0.866 E_m} \right] - \alpha_n,$$

$$\gamma_n = \alpha_n + \mu_n + \pi/6,$$

$$I_n = i_n, \text{ where } w_s t = (w_s T_n - \mu_n)$$

$I_{(n+1)}$ = the final value of i_n as computed in the previous, or (n+1)th, calculation used as the initial value in the nth calculation.

$I_{(n_f+1)}$ = the initial value of $I_{(n+1)}$ used in the first calculation where $n = n_f$. The value is assumed to be equal to the fundamental component of the load current.

$$= \frac{0.828 E_m}{Z_o} \cos (\alpha_{nf} + \theta_o).$$

t_{1n} = the smaller of the two quantities, t_{2n} or $[(D_c - D_g)w_s/(2s) - \mu_n]/w_s$, the time the thyristor reaches full conduction.

t_{2n} = $(w_s T_n - \mu_n)/w_s$, the end of the conduction period.

The following quantities as defined in Reference 2, Section 2.3 are stated in terms of input or output ratings for convenience.

$$w_s = 2\pi k_{f0}$$

$$E_m = \sqrt{2} E_s$$

$$Z_o = 27 E_s^2 / 16000 \text{ (KVA)}$$

$$\theta_s = \tan^{-1} (k \tan \theta_o)$$

$$Z = Z_o \cos \theta_o / \cos \theta_s$$

$$X_c = \frac{\pi k Z_o}{2.25 (k/z - \theta_o / \pi)} (V_{co} / E_s)$$

E_s = source L-N rms voltage

KVA = Output nominal rating

V_{co}/E_s = per unit voltage loss due to commutation.

$\cos \theta_o$ = load power factor

To complete the loss calculations, the energy losses are summed for all conduction periods in the half cycle

$$W = \sum_{n = n_f}^{n_e} W_n \text{ joules per cycle}$$

The energy loss is distributed among three thyristors in the positive bank of the cycloconverter, and the average power loss in each thyristor is

$$P = W f_o / 3 \text{ watts}$$

APPENDIX C

COMPONENT RADIATION EFFECTS STUDY

The assessment of the radiation effects literature has been continuing. Progress has been somewhat hampered in that the Radiation Effects Information Center (REIC) in Columbus has been inoperative during this interim; a new funding arrangement has just been initiated (mid-May) with NASA and DASA. Because the Center was forced to restrict its activities, the issuance of accession lists, reports, and memos for 1967 has been withheld, and, as of this writing, are still not available. Consequently, the most recent radiation effects literature has been unavailable insofar as the Center's services are concerned. It is hoped that this recent information will be available soon so as to permit at least a last minute appraisal.

Notwithstanding, the earlier literature has been, and continues to be, surveyed for radiation effects information on electrical components of interest in the design of space nuclear power systems. Thorough examination of the literature has revealed a paucity of pertinent information. Generally the number of studies concerned with components having performance ratings matching or even approaching those of interest are relatively few. Furthermore, the data provided by some of these specific investigations are not necessarily useful to the electrical design engineer. For example, some of the earlier experiments provide only pre-irradiation and post-irradiation measurement results and in many cases, the device has completely failed. At most, a damage level of complete exposure is thus specified, but does not define the threshold or mode of performance degradation. On the other hand, some recent experiments have been conducted in which several of the pertinent device parameters have been measured during the radiation exposure and the data are usefully presented in graphical and tabular form. Instances of the latter type, however, are in the minority.

The single-most important difficulty in conducting this literature assessment has been with the identification of specific devices tested. Easily one-half of the device codes or numerical symbols resist identification, which is obviously necessary to ascertain whether that device has performance ratings of interest. Aside from these missing identifications, the survey of information on silicon controlled rectifiers, silicon power rectifiers, and silicon Zener diodes is essentially complete. No information whatsoever is available on the high voltage (1000 V) SCR's and only one

low current 1000-V rectifier (0.1A) has been radiation tested. Only one 600-V rectifier has been studied and its current rating is an order of magnitude less than that of interest. Data on 1- and 10-W Zener diodes are somewhat better. The assessment of the resistor data is complete and essentially no additional data are required insofar as the neutron influences of this proposed mission are concerned. The evaluation of the silicon transistor, capacitor, thyatron, and integrated circuit information is in progress.