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ELECTRICAL COMPONENT TECHNOLOGY FOR
1/4 TO 10 MEGAWATT SPACE POWER

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ABSTRACT

Analytical data are presented for electrical power system components in advanced high-temperature, potassium Rankine nuclear space power systems. Power level and coolant temperature were used as independent variables to define combined minimum weight, maximum efficiency configurations based on an extensive background in the development of high temperature electrical materials, ac generators and motors, and power conditioning equipment for space applications. The data presented forecast electrical power system component design limitations and envelopes of minimum weight designs relative to such major systems parameters as temperature, shaft speed, voltage and frequency. Representative missions were analyzed for purposes of defining the ranges and types of electrical power needs and corresponding components.

INTRODUCTION

The redirection of the potassium Rankine cycle program, from a system development program (SNAP-50/SPUR) to a component technology and evaluation program, provided the opportunity to study the various options available on a system basis. Arbitrary decisions may have been encountered in previous programs as a result of scheduling and these decisions (on power characteristics, temperatures, etc.) may well have proved to be non-optimum for any one power level and certainly not optimum for all power levels.

A study, the results of which are presented in this paper, was undertaken on USAEC contract AT(04-3)-679 with the basic premise that the only need for a potassium Rankine cycle system in space is to produce electricity in the most "econom-

ical" fashion, economical referring to any of the various optimizing parameters normally considered: weight, volume, area, life. The over-riding guidance for this study was that the entire system was to be considered rather than a reactor surrounded by some electrical power equipment of secondary importance. Several classes of future missions were selected for study; earth orbital, lunar and interplanetary electric propulsion. The data will serve as a guide for long-range development goals of electrical component technology allowing immediate hardware development once specific missions are defined or conversely, provide the data necessary for determining the feasibility of a particular mission employing a potassium Rankine cycle system power supply. Megawatt space power technology is currently emerging into just such an era of component development and a broad guide such as this is helpful and timely in establishing a coordinated set of design goals for electrical components, materials, cooling systems, turbines, pumps, and payload.

The background and specific knowledge necessary to carry out such a study in a meaningful manner was available at the Westinghouse Aerospace Electrical Division through participation over the past decade in several high-temperature, high-power electrical component development programs. These programs covered (1) the alternator, pump motors, and frequency changers for the SNAP-50/SPUR system, (2) electrical and magnetic materials for 1600°F operation, (3) electrical systems in a potassium exposed environment, and (4) assorted kW power conditioning equipments for space applications. With this background for a foundation, the study could be carried out with the expectancy that the designs and data would be applicable to actual hardware configurations and design limitations thereof.

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The scope of the study was to carry out analytical design studies on alternators, ac motors, frequency changers, transformers, rectifiers, and distribution equipments applicable to 1/4 to 10 MWe power systems. Parametric data was generated to show minimum weight, maximum efficiency configurations for various system parameters such as frequency, speed, voltage, and coolant temperature. The reader is referred to the reports published on the contract, references 1 through 8, for data more specific than the summary data presented here.

Typical Missions and Electrical Systems

For most possible missions in space requiring power of this magnitude, a major portion of the load is represented by one or two types of loads, and this implies that the loads can directly influence the selection of megawatt system parameters. The mission objectives dictate the amount of power needed, the split between ac and dc, load frequency requirements, load voltage requirements, incident radiation and heat flux, and launch, landing, and start-up considerations. Thus, by defining the applicable missions and the associated loads, intelligent analysis may be made of such factors as generated voltage, transmission line parameters, cycloconverter output frequency,

cooling approaches, contactor configurations, and of course, overall system size and weight.

The purpose of the mission study was to analyze and design electrical system components and their parameters rather than to define potential missions. Therefore, the mission analysis involved defining, cataloging and evaluating information from previous mission studies. A total of five missions with a broad spectrum of requirements and objectives were considered. A tabulation of the various typical missions and their power demands is presented in table 1.

The lunar base differs from other missions in that there are no electric propulsion, surveillance or mapping loads to demand large blocks of power at high kilovolt-level dc voltages. However, the availability of an electrical system of at least 0.25 Mw capability would permit carrying out two important functions, that of regeneration of fuel for remote power needs and processing of lunar soil for water. It can be seen that for most missions, the great majority of the power (80 to 90 percent) is utilized as direct current. Most dc loads fall in the range of 20 to 20,000 volts. Only 30 kW (approximately) is needed at those voltages and frequencies that might presently be called "standard". Nearly 15 percent of system generating

Table 1. Typical Mission Load Requirements

Mission	Unmanned Interplanetary	Manned Interplanetary	Low-Orbit Space Station	Sync.-Orbit Space Station	Lunar Base
Typical Total Power	1.0-1.5 MW	4.0-10.0 MW	0.25-0.5 MW	0.5-1.0 MW	0.25 MW
1. Electric Thrusters	878KW 6.6KV 12KW -6.6KV 208KW 20v 4.5KW 30v 2.0KW 28v	8820KW Distributed as in Column 1	240KW 130v 4KW 120v ac	510KW 130v 12KW 120v ac	- -
2. Radar	154KW 20KV 2.0KW 28v	160KW Distributed as in Column 1	28KW 15KV 12KW 10KV 14KW 5KV 14KW 28v 4KW 120v ac	- - - - -	- - - - -
3. Communications	376KW 20KV 4.0KW 28v	376KW 20KV 4.0KW 28v	14KW 8KV 2KW 5KV 1KW 2KV 1.5KW 1KV 1.5KW 28v	45KW 30KV 25KW 20KV 25KW 10KV 10KW 3KV 35KW *	15KW 10KV 15KW 5KV 2KW 28v
4. Circulation Pumps	75KW 120v ac	510KW 120v ac	28KW 120v ac	41.5KW 120v ac	17.5KW 120v ac
5. Guidance & Controls	8.5KW 28v 1.0KW 26v 400Hz	8.5KW 28v 1.5KW 26v 400Hz	2.5KW 28v 2.5KW *	2.5KW 28v 11.4KW *	3KW 28v 5KW *
6. Generator Excitation	10KW (as generated)	105KW (as generated)	8KW (as generated)	12KW (as generated)	6.6KW (as generated)
7. Life Support		12KW 120v 400Hz 3KW 28v	4.2KW 120v 400Hz 1.8KW 28v	4.2KW 120v 400Hz 1.8KW 28v	16KW 120v 400Hz 9KW 28v
8. Miscellaneous			119KW (Laser) 1KW 3KV *	30KW 10KV 12KW ac	90KW 105v 165KW *

* ac(as generated)

capacity is needed for the electrical power system itself in the form of generator excitation, pumps, and other peripheral equipment.

The large power users on the referenced missions represent a fairly small group whose needs may be analyzed in some detail.

1. Circulation Pumps - Electromagnetic pumps require frequencies of 50 to 200 Hz, as well as voltages of 100 to 200 volts. Centrifugal pumps will likely be designed to operate at some point between 200 and 1000 Hz. Thus, with relatively higher frequencies desired for the generator, frequency changers will likely be needed to supply the pumps.

2. Electric Thrusters - The two most likely candidates for electric thrusters are arc jets requiring voltages near 100 volts dc and ion thrusters with 1 to 10 kV direct current. These require high-voltage, high-power rectifiers.

3. Radar and Communications - The majority of this power is utilized in the 1 to 30 kV dc range with only a small amount at standard ac and dc values. This also requires appropriate rectifiers.

4. Generator Excitation - This power can be supplied as generated since it will be rectified and controlled by the generator regulator.

Transmission distances may range from 4 to 5 feet between generator and main contactor, to 100 feet for loads in a manned space station, to 1000 to 10,000 feet for a lunar base. Contactors must be capable of interrupting the voltage and power levels described previously.

A part of the mission study was to determine the specific weights of the complete power systems up to 10 MWe and 40,000 hours life. With the system specific weights, the combined values of near-minimum component weight and near-maximum component efficiency could be selected to give minimum system weight. This combination of component weight and efficiency is necessary since they usually do not occur simultaneously. The system specific weights determined ranged from 9.9 to 30.0 lbs/kWe depending on the coolant temperature, rating, mission and lifetime. The weights are expected to correspond to refractory system of the future.

Alternators

The specific type of alternator studied was the radial gap, homopolar inductor alternator. This particular type of alternator has previously been found to be most suited to the special requirements and has undergone considerable development in the past (SNAP-50/SPUR, SNAP-8, Brayton Cycle). A

typical configuration is shown schematically on figure 1.

The present study was carried out at ratings of 0.4, 1.2, 6, and 12 MVA over ranges of 500° to 1400°F coolant, 60,000 to 1000 RPM, 400 to 3200 Hz, and 250 to 2140 volts (L-N). These particular parameters were selected based on past design experience and past alternator and mission studies. Approximately fifteen hundred designs were examined within these ranges. The specific purpose of the study was to determine the frequencies, speeds, and voltages which gave lowest system weights while also staying within practical design limitations. This included use of available materials or new materials being developed and their associated strength and temperature limitations. The (effective) system weight of the alternator was evaluated as an electrical weight plus a weight penalty. That is,

Electrical Weight plus System Weight Penalty*

$$= W_{ge} + (S_g + S_L)kW_{gL}, \text{ lbs., where:}$$

W_{ge} = electrical weight of generator (excludes inert weights such as structures, terminals, bearing housings, end bells, etc), lbs.

S_g = specific weight of system supplying shaft power to generator, lbs/kW

S_L = specific weight of auxiliary cooling system rejecting generator losses, lbs/kW

kW_{gL} = generator losses, electrical and frictional, kW

The weight penalty represents the weights of both the power source and the cooling system that must supply and dissipate the alternator losses.

A multitude of possible choices of materials and electrical or mechanical design variables are available to the generator designs. These were either initially chosen from experience and held fixed throughout the design study or separate studies were carried out to establish them. The pertinent variables and constants chosen are summarized in table 2 according to the coolant temperatures or ratings considered. Separate rotor material selection studies were carried out because of the significance the rotor material choice usually has on the final configurations and system parameters such as speed and frequency.

The combinations of frequency, speed, and voltage giving minimum weight were determined via an iterative cycling process whereby two of the three were fixed and the third was varied. This was repeated then for the next two variables using the (minimum weight) values selected from the pri-

* The same type of system weight evaluation was applied to the other components when appropriate.

Figure 1. Typical Alternator

Table 2. Alternator Design Parameters

Stator Materials⁽⁹⁾

Frame	- Hiperc-27 forgings
Stacks	- 4 mil Hiperc-27 sheet, plasma arc sprayed alumina interlaminar insulation
Windings	- @ 500° and 800°F coolant, Inconel-clad silver with 0.011-inch-thick E- or S-glass Anadur
	- @ 1100°F coolant, dispersion-strengthened CuBe alloy with 0.008-inch plasma sprayed alumina
Slot Insulation	- 98.5% pure alumina, 0.018 inch thick
Bore Seal	- 99.8% pure alumina or Beryllia depending on temperature

Rotor Materials⁽⁹⁾

@ 500°F Coolant	- H-11 steel @ 45R _c
@ 800°F Coolant	- H-11* steel @ 45R _c , NIVCO alloy, 1AS2 alloy ⁽¹⁰⁾
@ 1100°F Coolant	- NIVCO alloy, 1BS1* alloy ⁽¹⁰⁾
@ 1400°F Coolant	- Dispersion-strengthened cobalt alloy ⁽¹⁰⁾

* indicates material selected from choices shown

Design Variables⁽⁶⁾

Armature Current Density	- @ 500°F coolant, 7000 amps/in ²
	- @ 800° and 1100°F coolant, 6000 amps/in ²
Field Current Density	- 4000 amps/in ²
Pole Embrace	- 67%
Phase Belts	- 60°, 2/3 pitch
Rating (mva)	0.4 1.2 6.0 12.0
X _d , P. U.	1.0 1.2 1.3 1.3
Radial Gap, inches	0.1 0.125 0.229 0.275
Bore Seal Thickness, inches	0.065 0.08 0.129 0.175

or study cycle. Once the frequencies, speeds and voltages giving minimum weight were determined, the whole cycle was repeated with the two fixed variables corresponding to the selected (minimum weight) values from the initial cycle. The results of this cyclic screening process are briefly summarized in table 3 and figure 2. The speeds shown are within the stress limits of the selected rotor materials by a reasonable safety margin. The approximate maximum speeds that the alternators could be operated at are illustrated on figure 3. The voltages selected are all in the 500 volt range. This is based on the result that, at 250 volts or below, the system weight increases significantly and at 1000 volts or above, the system weight gains are negligible compared to the added complexities of high-temperature, kilovolt insulation systems and winding configurations requiring series turns in the slots⁽⁶⁾.

Separate high-temperature designs were evaluated using special rotor materials developed specifically for 1400°F or above temperatures⁽¹⁰⁾. In general, it was found that even with these special

Table 3. Summary of Generator Parametric Study, Selected Speeds, Frequency and Voltages

Generator Rating* (MVA)	Coolant Temp. (°F)	Selected Frequency (Hz)	Selected Speed (RPM)	Selected Volts (L-N)	Electrical Weight (LBS)	Efficiency (%)
0.4	500	2000	40000	500	294	91.3
1.2	500	1600	24000	500	1008	92.3
6.0	500	1200	12000	500	5257	91.9
12.0	500	1200	12000	500	9966	92.5
0.4	800	2000	30000	500	329	91.2
1.2	800	1600	19200	500	1151	92.1
6.0	800	1200	12000	500	5317	92.4
12.0	800	1200	8000	500	16619	93.5
0.4	1100	1500	18000	500	536	91.8
1.2	1100	1200	12000	500	1749	92.4
6.0	1100	800	6857	500	10644	92.8
12.0	1100	800	5333	500	24906	93.2

* All at 0.85 p.f.

Figure 2. Electrical Weight

materials, the strengths limitations were sufficiently low -- e.g., 15,000 psi -- to prohibit high speed operation. The result was a low speed (4000 RPM at 1.2 MVA) high specific-weight design as illustrated on figure 2. One of the general conclusions drawn from the study and illustrated on figure 2 is that, for the high-speed, large ratings of the study, the Fe-base alloys such as H-11 give the minimum system weight designs but were limited to coolant temperatures of approximately 800°F. Developmental alloys such as 1AS2 of table 2 show promise for raising this limit to approximately 900°F. At approximately 900° to 1100°F, Co-base alloys such as 1BS1 or NIVCO must be used

Figure 3. Maximum Allowable Speed

but since they have lower magnetic permeability and strength, the speeds must be decreased and higher specific weights result. Above 1200°F coolant, the special dispersion strengthened alloys must be used. Of the two properties, magnetic or strength, it appears that it is the lower mechanical strengths which are most influential in creating the high specific weights. That is, many of these higher temperature alloys apparently have sufficient magnetic capability but insufficient mechanical strength. Until such time that this occurs, little appears to be gained in operating the alternators at very high coolant temperatures for the sake of minimizing auxiliary cooling system weights.

Separate alternator conceptual designs were evaluated in greater detail near the end of the study. Three important results came out of these detailed studies. One was the discovery that the radial gaps of table 2 should be increased for optimum electrical design to the extent that bore seal thickness could be increased to 0.07, 0.102, 0.212 and 0.290 inches for the four ratings. Inas-

much as these thicknesses were initially selected according to forecasted bore seal manufacturing capabilities, the increased gap means that the bore seals could be thickened somewhat to reduce the development effort required to fabricate them. The second result was that the general stress criteria used in the screening studies gave conservative results when stresses were analyzed in detail. Thus, limiting speeds of figure 3 should be conservative.

The third important result is illustrated on figure 4 which shows that the minimum weights occur at a finite rating less than 10 MWe. Thus, any technology programs aimed at developing alternators for multimewatt systems may be based on redundant alternators of only a few megawatts rating. This has the obvious advantage of the most reliable configuration being the lightest.

AC Pump Motors

As indicated previously, the motors having the most influence on the electric power system are those on the circulatory pumps. Thus, the ac motors studied were limited to those applicable to the centrifugal pumps of the prime mover systems. The particular type of motor considered was a poly-

phase, strap wound, canned induction motor. This type of motor had been determined to be most suitable to the particular requirements in previous systems (SNAP-50/SPUR) and has undergone development in the past. A typical configuration is shown schematically on figure 5.

The present study was carried out at ratings of 5, 30, 60, 100, and 250 hp over ranges of 500° to 1100°F coolant, 24,000 to 4800 rpm, 200 to 2000

Figure 4. Alternator Weight Comparison 800°F Conceptual Designs

Figure 5. AC Motor Configuration

Hz and 120 to 1000 volts (L-N). Again, the particular ranges of variables were selected on past experience and forecasted mission requirements. Over 500 designs were investigated within the ranges shown. In addition to determining the frequency, speed, and voltage giving minimum system weight, corresponding power factors were determined. The data was directed toward identifying characteristics of canned motor-pump packages for comparison with electromagnetic pumps or turbine driven pumps, or for identifying motor development requirements.

Table 4. Pertinent Motor Design Parameters

<u>Stator Materials</u> ⁽⁹⁾	
Frame	- Tantalum T-111
Laminations	- Hiperco-27, Aluminum Orthophosphate or plasma arc sprayed alumina interlaminar insulation
Windings and Slot Insulation	- Same as alternator of table 2
Bore Seal	- Same as alternator of table 2
<u>Rotor Materials</u> ⁽⁹⁾	
Can	- Tantalum T-111
Conductor Bar and End Ring	- Dispersion-strengthened CuBe
Laminations	- @ 500°F coolant, Hiperco-27
	- @ 800° and 1100°F coolant, NIVCO
Rotor Shaft	- Tantalum T-111
<u>Design Variables</u> ⁽⁵⁾	
Maximum Torque/Rated Torque	- 2.25
Stator Winding Current Density	- 10,000 amps/in ²
Rotor Can Thickness	- 0.015 inch
Bore Seal Thickness	- Alumina, 0.024" @ 4 inches to 0.072" @ 12 inches diameter
	- Beryllia, 0.070" @ 4 inches to 0.110" @ 12 inches diameter
Radial Running Clearance in Gap	- 0.010 to 0.020 inch

Like the alternator, if not more so, special attention had to be paid to selection of materials and mechanical or electrical design variables having a direct influence on the outcome of the study. Approximately 140 preliminary motor designs were analyzed for purposes of establishing the design parameters and limitations prior to executing the screening studies. A summary of the selected values is given in table 4. Because the application of induction motors to nuclear space power systems requires a significant extension of conventional motor technology to elevated temperatures, close attention was given to the interrelationship between magnetic, electrical and mechanical design. Although the same holds true for the alternators above, the interrelationships are usually more sensitive in the motor designs. Also, because the motors would most likely find use in a variety of system loops containing either potassium, lithium or NaK, the materials selection for the exposed surfaces had to be such that they would be compatible with any or all of the three. This leads to the requirement for refractory metal alloys and the subsequent choice of T-111 alloy (Ta, 8W, 2Hf).

The study was carried out in an iterative cycling process similar to that employed on the alternator study. The results of the studies are summarized in table 5. The specific weights and efficiencies are typical. The selected frequencies all fell within the 400 to 800 Hz range from both the standpoint of the motor as an individual unit

Table 5. Recommended Frequencies, Speeds, Voltages for Specified Rating and Temperatures

Motor Rating, HP (kWe)	5 (3.7)			30 (22.4)			60 (44.7)			100 (74.6)			250 (186.4)		
Coolant Temperature (°F)	500	800	1100	500	800	1100	500	800	1100	500	800	1100	500	800	1100
Frequency (Hertz)	400	400	400	400	800	600	800	800	800	800	800	800	600	600	800
Synchronous Speed (rpm)	24000	24000	24000	24000	24000	18000	24000	24000	16000	24000	24000	12000	12000	12000	8000
Voltage (Volts L-N)	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
Specific Electrical Weight (lbs/hp)	2.06	2.39	2.31	0.92	0.87*	1.33	0.5*	0.55	0.87	0.48*	0.52	0.79	0.54*	0.57	0.88*
Efficiency (Percent)	76.0	72.5	63.1	83.8	74.4*	74.5	81.5*	83.1	77.0	85.0*	84.8	82.0	89.1	89.1	80.8*
* Estimated values															

and as a part of an "optimized" system. Four-hundred Hertz is preferable at 5 to 30 hp and 600 to 800 Hz is preferable above 60 hp. The number of poles giving minimum weight designs was generally between 2 to 8 poles for the speeds selected. The selected synchronous speeds are generally between 12,000 and 24,000 RPM except for the 1100°F, 250-hp design which is 8000 RPM. The higher speeds gave decreasing motor weight provided the designs did not exceed other limitations relative to cooling and strength.

The influence of the voltage on component or system weight over the 120- to 1000-volt range was found to be fairly minor as it was on the alternator with one exception; that is, on the motor, this minor influence extends down to the 120-volt level. Thus, the selected voltage is the lowest possible for reliability's sake, 120 volts for all ratings and temperatures. In reality, however, the choice of voltage may be whatever is required to fit the desired system up to 1000 volts for ratings over 60 hp. For example, an alternator output voltage of 480 volts connected directly through a cycloconverter would result in a motor input voltage of about 360 volts and an intermediate transformer would not be required unless higher line voltages were desired to minimize line losses.

Frequency Changers

Circulation of the system heat transfer fluids requires the use of ac pump-motors or electromagnetic pumps. For efficient operation, frequencies are needed well below those desired for the generator output. Since these loads do not represent a large portion of the total load, frequency converters are required. This conversion from a relatively high frequency to a low frequency can be accomplished most efficiently and reliably by the use of a static cycloconverter which converts the ac input frequency to a lower output frequency.

The basic cycloconverter power circuit consists of a pair of three-phase, half-wave thyristor bridge circuits for each output phase. The pairs are connected in reverse parallel and the firing of each thyristor is controlled in such a way that the additive effects on each output phase result in approximately sinusoidal voltages. The evaluation was concentrated primarily in the area of the power circuits because these circuits contribute by far the largest share of the component weight, dissipate the greatest losses, vary directly in weight and size with rating, and are the most affected by variations in voltage, current and frequency. Typically, the controls would consist of a reference generator providing a sinusoid, at desired output frequency, to operate through logic circuits to fire the thyristors in the proper sequence.

The analysis of potential user loads indicated that cycloconverter power requirements would range between 5 and 500 kVA with power factors varying between 0.5 and 0.75 in most cases. Output frequencies fall between 100 and 1000 Hz and, therefore, a range of 50 to 2000 Hz was studied to adequately show parameter trends. Similarly, an output voltage range of 200 to 1500 volts was needed to cover the requirements spectrum. Coordination with generator frequency studies dictated an input frequency range for comparison of 800 to 3200 Hz.

The approach used was to base all design comparisons on available, state-of-the-art components derated to a maximum 50 percent operating voltage stress to represent realistic requirements for high reliability apparatus. The resultant weight comparisons are based only on electrical weight and cooling weights since support structure and packaging weight would vary widely with the application. Meeting the higher output ratings of 250 and 500 kVA requires the paralleling of thyristors. This was done by utilizing the commutating inductors to cause load sharing between thyristors. A cold-plate cooling approach was assumed with the relatively low temperature organic coolant used because of temperature limitations of the semiconductors.

To determine the influence of load rating, an analysis was made of weight and efficiency as a function of rating for a typical design of 200-volt, 2000-Hz input and 150-volt, 400-Hz, 0.7 PF output. The weight and efficiency variations are shown in figure 6. It can be seen that above 125 kVA, weight increases nearly linearly with little gain in efficiency. The effect of various values of input voltage on weight and efficiency of a typical 50-kVA unit are shown in figure 7. Weight is seen to increase rapidly with increasing voltage while there is little

Figure 6. Specific Weight and Efficiency as a Function of Rating for Frequency Changers

Figure 7. Input Voltage - Volts

Figure 8. Output Frequency - Hertz

effect on efficiency. Figure 8 shows that for varying values of output frequency, little weight savings can be gained by going above 400 Hz. This general trend was found to be true for all input frequency values although there was a weight savings with higher input frequencies up to about 3000 Hz. Specific weights were found to decrease with power rating as might be expected but the rate of decrease was not as great above 100 kVA because of the need to parallel thyristors. Since the presently available thyristors are the limiting design factors from both the electrical and thermal standpoints, an analysis was made of the developments to be expected in switching devices in the next 20 years. Although somewhat speculative, the following appear to be reasonable improvements to obtain in the next decade.

1. Increased voltage capability from present 1000 to 1750 volts.
2. Increased junction temperature capability from 125° to 150°C.
3. Increased di/dt and dv/dt capability by a factor of 100.

4. Decreased packaged weight to 25 percent of present values.

Gas and vapor tubes presently under development show promise for increased operating temperatures. However, their use in cycloconverters based on present data would result in considerably heavier units as shown in figure 9.

Rectifiers

Since the generator power is in the form of ac, dc power must be provided through the use of static rectifiers. The dc loads to be supplied vary from relatively small electronics and instrumentation loads up to rectification of over 85 percent of the generated output in the case where dc transmission to the dc load is used. For most missions, few dc loads could be supplied by direct rectification of generator output. Instead, the rectifier design can and should be integrated with that of the transformer needed to provide the proper voltage conversion.

Rectifier designs considered were limited to various 6 and 12 phase interconnection approaches. As the number of phases increases, the electrical performance improves but the mechanical design becomes more complex. Multi-phase operation improves regulation, waveshape, power factor, and transformer utilization factor. However, the comparisons determined that the 12-phase circuits did not increase electrical performance to a degree to justify the increased size and weight and reduced reliability in space power applications. To meet the very high voltage requirements, series strings of diodes are needed and resistor-capacitor networks are used to provide proper voltage division. In order to provide representative realistic designs, the following guidelines were used:

Figure 9. Gas Tube Frequency Changer Specific Weight and Efficiency as a Function of Rating

1. Rectifier components must be state-of-the-art.
2. Diode voltage rating must be at least 2.25 times operating value to allow for voltage transients and high reliability.
3. The diode assembly must be capable of meeting a 5 second 300 percent overload.

Mechanical design efforts were centered primarily on providing adequate cooling for the components. A cold plate with organic coolant was assumed. Based on analysis of typical loads, power ratings of 25 kW to 10 MW were considered with dc voltages of 120 volts to 30 kV. Demands below 25 kW were not considered to have significant influence on system design. Voltages below 120 volts in the above power range were found to be primarily heater loads that could be supplied ac. For loads above 500 kW, only voltages of 5 to 30 kV were required.

Weight and efficiency as a function of rating were computed for voltages of 0.12, 1, 5, 10, and 30 kV dc. For designs above 1 kV, efficiencies were found to increase slightly with rating but still varied only between 99.3 and 99.7 percent. For the 120-volt designs, efficiencies ranged between 98.7 and 98.9 percent. In general, weight was found to increase with rating with the rate of increase becoming much greater above 200 to 300 kW. A curve showing specific weight for the 5000-volt designs (selected as being typical) is shown in figure 10. Weight of the rectifiers at a given power level increased with increasing voltage as can be seen by comparing the 500-kW designs shown in table 6.

Gas and vapor tube rectifiers currently under development promise some performance advantages over semiconductor designs and were therefore included in the comparative analysis. They are capable of much higher temperatures (932° to 1382°F) and can withstand at least 30 kilovolts as single units without paralleling. They were,

Figure 10. Specific Weight as a Function of Rating for 5000-Volt Output Rectifier

* Some "Gradual Change Data" was found in sources from the SNAP-8 Radiation Effects Test Program. The sources are listed in reference 4.

Table 3. Packaged Weights of Silicon Diode and Gas and Vapor Tube Rectifier Systems

Rating	Packaged Weight - Pounds					
	1000 Volt DC		5000 Volt DC		30000 Volt DC	
	25 kW	500 kW	25 kW	500 kW	500 kW	10000 kW
Silicon Diode	6.8	11.8	23.1	71.4	115.5	636.5
Gas & Vapor Tube	76.41	448.63	62.3	113.33	167	477.11

however, found to be considerably heavier as is shown in table 6. These tubes do promise increased radiation resistance and therefore greater flexibility in location as part of a nuclear system.

Radiation Effects

The effects of nuclear radiation on electrical components can greatly affect their use in a space nuclear power system. Radiation susceptibility can limit the proximity of a power conversion device to the nuclear source, add weight to the system through increased shielding needs, or severely limit the operating life of a given item of equipment. Previous component radiation effects studies appeared to be of only limited use to the electrical designer. In general, they defined the cumulative radiation levels at which the component lost its capability to function rather than to define the gradual changes* that would be found in a typical system. In addition, there appeared to be only a small amount of data applicable to those power-handling components that would find use in a large space nuclear power system.

For these reasons, an analysis was made of the availability of radiation effects data of use to the designer of equipment. The primary purpose of the study was to determine if existing information was at all adequate. The study was limited to the effects of radiation on those components used for the generation, control, conversion and utilization of electricity; namely silicon controlled rectifiers, silicon power rectifiers, silicon power transistors, capacitors, resistors, silicon zener diodes, vapor and gas-filled thyratrons and rectifiers, integrated circuits and electrical insulation materials. For quantitative analysis, a mission of 10,000 hours was assumed with radiation levels of 10^7 rads gamma and 10^{13} nvt fast neutrons.

A search of the literature indicated that comprehensive information on radiation damage effects for many components of interest was not available. Reference 4 contains a listing of 181 sources of radiation damage effects information for the com-

ponents of interest. In general, it can be stated that there is a need for additional testing and evaluation to draw abreast of state-of-the-art developments in high-voltage, high-current semiconductors.

Transformers

Transformers are needed to provide the desired load voltage from cycloconverters, provide proper rectifier compatibility and input voltage, and transform the generated voltage to values such as might be used efficiently in power transmission. Because of potential load requirements, both single-phase and three-phase transformers were considered. Because of the myriad of possible combinations of the various parameters affecting transformer design, it was decided to perform separate evaluations of the major parameters affecting electrical performance. These include input and output voltage, kVA rating, and coolant temperature. To assure realistic designs, voltage transients of 160 percent rated value were assumed along with overloads of 300 percent for 5 seconds.

The required transformer ratings can range from below 25 kVA to 10 MVA for boosting voltage at the source for transmission purposes. The decision was made to evaluate single-phase units in a range of 10 to 1000 kVA and three-phase units between 25 kVA and 10 MVA. Coolant temperatures of 500°, 800° and 1100°F were selected for the evaluation on the basis of available materials and compatibility with other system analyses. Input voltages ranged from 500 to 2140 volts L-N in accordance with generator evaluations while output voltages covered a range of 30 to 20,000 volts in keeping with the user loads analysis. Frequencies considered were 400, 800, 2000, and 3200 Hz, also based on analyses of other components in the system. Selected state-of-the-art materials for

the various operating temperatures are presented in table 7. For the best cooling, the coolant must be passed through the coils. This was assumed to be done by tantalum T-111 coolant ducts in the coils, electrically insulated from the coils by alumina or beryllia sheet. Potassium was assumed to be the coolant. Cooling was a major consideration since increased temperature results in increased losses. Similarly, increased core and conductor sizes decrease losses but increase weight.

Input voltage variations were not found to substantially affect transformer weight. Output voltage did produce a greater effect with minimum weight appearing between 400 and 900 volts L-N for all coolant temperatures. Above 2000 volts, the weight increase for all frequencies was nearly linear with voltage. As would be expected, there is a direct tradeoff between efficiency and weight. In most cases, the added weight to obtain about 97 to 98 percent efficiency, compared to 93 percent for example, does not seem significant, especially when one considers the reduced cooling requirements. Specific weights as a function of rating for three-phase designs at 500°F coolant are presented in figure 11. A comparison of weight as a function of rating for 400-Hz designs at various coolant temperatures is presented in figure 12.

Figure 11. Three-Phase Transformer Specific Weight as a Function of Rating for Various Frequencies

Table 7. Selected State-of-the-Art Materials at Various Operating Temperatures

COMPONENT	500° AND 800°F COOLANT	1100°F COOLANT
1. Conductors	Inconel 600-Clad Silver	Dispersalloy-Strengthened Copper
2. Magnetic Core	Hipersil	Hiperco 27
3. Coolant ducts & plate	Tantalum T-111	Tantalum T-111
4. Coil Rigid Insulation	99.5% Alumina	99.8% Beryllia
5. Potting Component	Boron-Nitride	Boron-Nitride
6. Coil Interlayer Insulation	Boron-Nitride Fiber Paper	Boron-Nitride Fiber Paper

Transmission and Distribution

The distribution system analysis must consider all possible combinations of electrical parameters to be encountered between the source and the loads. Parameters considered were: frequencies from dc through 3200 Hz, three-phase ac voltages from 120 to 20,000 volts L-N, dc voltages of 100 to 30,000 volts; and currents from 50 to 500 amperes. In addition, where active cooling was needed, available coolants were considered to be between 500° and 1100°F. This portion of the

Figure 12. Three-Phase Transformer Specific Weight as a Function of Rating for Various Coolant Temperatures

study considered two items, (1) transmission lines to carry power, and (2) contactors to control distribution.

The analysis of transmission lines on a parametric basis is very difficult because of the complex interrelationships of the parameters. This includes conductor shape, solid or hollow conductors, cooling approach, spacing, and material selection. Previous analyses have selected one value of radius ratio for a parametric analysis. This is the conductor outside radius divided by the radius of current penetration resulting from skin-effect. For this analysis, however, the radius ratio was computed by iterative procedures for each value of frequency and conductor resistivity. The results of the analysis showed that either dc or 3200 Hz ac (the highest frequency considered) give the best performance from a weight/loss standpoint. Likewise, high voltages and low current density values are highly desirable. Hollow, round conductors were found to be the most desirable from the standpoint of mechanical strength and cooling.

Contactors are required in a system to provide protection against continued faults or overloads, to permit manual or remote application or removal of power on a load bus, and to permit transfer of power between buses. Of the various available types of contactors, the most desirable from the standpoint of weight and size is the vacuum contactor. However, it is best applied where voltages can be kept very high. Existing dc designs are limited to approximately 10 amps maximum. Although ac units are presently available only at ratings up to several hundred amps, technology for 1200 amps capability is presently available. These contactors use tungsten butt-type contacts. Development is presently underway to attain a capability of 1800 amperes at 1500 volts, 2000 Hz, as well

as 20 amperes at 10,000 volts dc. Presently existing lightweight contactors are limited to between 60 and 100 kVA.

Analysis of contactors showed weight to decrease rapidly with increasing voltage up to approximately 2 kV where little is to be gained by increasing voltage. Analysis of projected contactor technology currently capable of being fabricated (rather than available hardware) showed that for ratings of 50 to 2000 kVA, weight would only vary between 5 and 15 pounds above 2 kV. However, at 500 volts, the 2000 kVA unit weighs 80 pounds and the 1000 kVA unit weighs 20 pounds.

CONCLUSIONS

Because of the many possible trade-offs between power system operating conditions and mission loads, it is impossible to arrive at one set of system parameters giving minimum weight. However, there are several compatibilities between the various minimum weight component configurations. The choice of alternator frequency and voltage on the basis of the alternator requirements alone appears desirable from the total system standpoint (with these large ratings) except for voltage for direct distribution. While future insulation developments to increase voltage capabilities to kV levels should allow alternator designs more compatible with distribution system voltages, the added complexities of series winding rigid or glass insulation systems will probably preclude their use. The speeds of these high-rating alternators are sufficiently high in the 500° to 800°F coolant range to allow efficient, minimum weight turboalternators to be produced. Above 800°F, the limiting strengths of the available magnetic rotor materials result in lower speed operation, heavier alternators, heavier systems, and most likely, compromises in the desirable turbine speeds.

The desirable frequencies and voltages of the ac pump motors appear compatible with the systems as a whole. The desired synchronous speeds appear high from the standpoint of the centrifugal pumps and some design tradeoffs may be required.

For the cycloconverters, silicon-thyristors are the best approach at present because of lower weight and better availability. Little is to be gained by building cycloconverter modules above ratings of 125 kVA or with output frequencies much above 400 Hz. Higher ratings can be obtained by paralleling modules. Also, a relatively low voltage power source is desirable. It appears that significant improvements in high power cycloconverter design can best be served by rapid advancements in the switching component state-of-

the-art. Likewise, for high power rectifier designs, the development of silicon diodes of much greater voltage capability will reduce the number needed in series for high voltages and thereby decrease weight, not only by elimination of diodes but also by removing the associated voltage division networks.

It was shown that transformer input voltage variations have little effect between 500 to 2140 volts L-N. Frequency should be relatively high although 3200 Hz shows little advantage over 2000 Hz. Output voltages should preferably be below 2000 volts although in general this will be governed by the loads. The technology to meet transmission line requirements for these systems appears to be readily available. Required contactors are not available however and present development efforts should be continued and expanded, especially in the areas of higher current capability.

From the standpoint of overall mission load requirements and component development status, programs aimed at electrical power systems in the one megawatt range appear likely to yield the most applicable technology for future missions. When and if, tens of megawatts of space electric power are needed, the power systems could be built on the paralleled megawatt systems.

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