Optimization of Thermionic Generator Systems of High Reliability

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Summary

Thermionic generators using radioisotopes as primary sources of energy are being considered for application to future space missions. The reliability of a matrix of a large number of thermionic converters has been studied by J. R. Long of the Lawrence Radiation Laboratory and found satisfactory.

In this paper, an optimization of the generator system is carried out for a thermionic generator with a power output of 300 watts. Allowance is made for the efficiency of the dc-dc power conditioners that are currently available. The system chosen for the study has from 9 to 15 individual thermionic energy converters. These are interconnected to form either a flat or a three-dimensional network, and their characteristics are linearized so that each converter can be represented either by a Thévenin's or a Norton's equivalent circuit. The system efficiency is determined from its configuration, the efficiency of the power conditioner, and from the efficiencies of the individual converters, which depend on their output power.

Degradation in the performance of the system is calculated for abrupt open- or short-circuit failures of individual converters. Gradual degradation of converters, such as that occurring when emitter temperatures or cesium reservoir temperatures change, is also considered.

A generator system of 15 individual thermionic cesium diodes was selected for detailed studies of the degradation and reliability. The system is considered realizable with the existing technology in thermionic energy conversion. The system has an adequate reliability and can fulfill a mission successfully if it is designed with a contingency factor of approximately two.

Introduction

Up to the present, research and development in thermionics have been directed primarily at relatively large diodes for two reasons:

1. Much of the investigation was of a basic nature, with the purpose of determining performance characteristics of emitter and collector surfaces, and understanding problems related to materials. These problems are easier to understand for reasonably large geometries.

2. Much of the effort was directed at obtaining high performance and high conversion efficiency, and these are most easily obtained with large diodes.

For power supplies of large total capacity, there is little question that the optimum diode will indeed be large. The maximum size of the diodes will probably be limited by high-temperature dimensional stability problems, since it would be necessary to hold accurate clearance tolerances over increasingly large high-temperature emitter and collector surfaces.

For small power supplies, however, thermal efficiency of the individual diodes is not necessarily the most important design criterion. For a spacecraft or a landing capsule, it might be necessary to develop a minimum weight power supply, which can supply as low as 100 - 300 watts, at 26 volts or more, with a given reliability, over a given mission length. Since the individual diodes have an output of about 0.5 - 1.0 volt, and the efficiency of the power conditioner decreases rapidly with decreasing input voltage, it is desirable to use several series strings in parallel, and to use cross connections between the several series strings. One is hence pushed towards a multiple-diode network, which, for a system of limited power capability, forces one to small diodes, with an efficiency which is relatively low compared to that of the larger diodes.

The reliability of various thermionic-powergenerator systems having two-dimensional arrays of thermionic energy converters was studied extensively by Holland of General Dynamics. The study was extended to systems of three-dimensional arrays by Long of the Lawrence Radiation Laboratory.

We have studied several generator systems having three-dimensional arrays that have a specific power output of 300 watts. This power output was selected on the basis of the expected power demand for unmanned exploration of deep space, and on the basis of available technologies in thermionic energy conversion. Factors such as reliability, power degradation, thermionic converter efficiency, power-conditioner efficiency, and system efficiency are considered for the selection of a desirable system. The power degradation of the system was studied for cases of abrupt short circuit, abrupt open circuit, as well as of gradual degradation of individual diodes.
converters due to changes of emitter temperatures or cesium reservoir temperatures.

In particular, a system with 3 parallel legs having 5 converters in series, each operated at 0.5 volt under a load of 25 watts per converter, would be adequate if the individual converters have a reliability factor of 0.99. However, a contingency factor of 2 must be used in designing a system if the individual converter has a reliability factor of 0.95.

Requirements for controlling the emitter and cesium reservoir temperatures are found to be far less stringent in the multiconverter system than in a single converter.

Converter Array

For deep space exploration to be successful, power sources on board the spacecraft must be reliable, efficient, and preferably operated from solar-independent primary energy sources. To achieve high reliability, a system of many individual power units forming an array (or matrix) must be used. A high efficiency that is required from considerations of system weight and costs demands that the output voltage of the generator system must be large enough to enable efficient integration with an appropriate power conditioner. Since an individual thermionic energy converter has output voltages of approximately 0.5 volt under load, at least three such converters must be connected in series so that the raw power can be power conditioned efficiently. In fact, an immediate development of power conditioners that are operable at ambient temperatures in a 500°K range is needed for the systems to become useful.

In this study the selection of a converter array was made on the following conditions: 1) power degradation must be less than 15% of the nominal power output when one converter in the system fails; 2) converter failure can be either an open circuit or a short circuit; 3) the system efficiency must be comparable with that of solar-cell power systems; and 4) elements in the system including thermionic energy converters are linear in their volt-ampere characteristics. The first and second conditions necessitated the series-parallel connections for an array. Moreover, the system branches had to be interconnected with other series branches at many points. The third condition limited the numbers of individual converters in a system with a given power output (300 watts) since the efficiency of an individual converter lowered as its physical size became smaller. The fourth condition was imposed to ease the calculation of the system output. Linearization will not cause unreasonable errors, however, as long as the operating point of each element does not move appreciably.

Since the efficiency of an individual converter decreases rapidly as its power output capacity decreases below 20 watts, a minimum of 15 converters was considered to form the generator system. Then the power output available from a system on either open- or short-circuit failures was calculated. The system was interconnected so as to form a three-dimensional array such as is shown in Fig. 1.

Available output power is shown in Fig. 2 as a function of the number of parallel branches of a system with 15 and 16 converters. It is clearly seen that as the number of parallel branches increases, the smaller is the effect of a single open-circuit failure. The reverse is true for a short-circuit failure. Also, the effect of interconnecting resistances is seen; if the resistances $R_j$ are zero (i.e., the parallel branches are closely coupled), the short-circuit failure is most damaging to the system. However, the open-circuit failure is most damaging if $R_j$ is infinite (i.e., the parallel branches are independent of each other), as is expected. On the basis of the results shown in Fig. 2 we have selected a system of 3 parallel branches. Subsequently the effect of the number of series converters in each branch was examined; results are shown in Fig. 3. Again, contrary effects of $R_j$ were observed on the available power in cases of open- or short-circuit failures. It should be pointed out that the magnitude of the load resistance does not influence the output power greatly because the output power is maximum over a broad range of load resistance about the matched value and because the internal resistance does not change appreciably when a single failure occurs in the system of many converters. Therefore, calculations were made on the assumption of a matched load for simplicity.

If one assumes an equal probability for
occurrences of open-circuit or short-circuit failures, it is now obvious that the interconnecting resistances must be optimized to achieve a satisfactory performance. The optimum value for these resistances was three times the internal resistance $R_i$ of each thermionic energy converter when interconnections were made in $n$-circuits in order for the relative power to be equal on either an open- or short-circuit failure. If the connections are in $y$, each resistance just equals the internal resistance of the converter. In any case, the available output power is 83% of the nominal power output for either an open- or short-circuit failure occurring in one of the converters nearest to the output terminals (first- or fifth-level converters), whereas the available power can be as small as 8% if an open-circuit failure occurs in one of the third-level converters. No further attempts were made to optimize interconnections to achieve equal output power for cases of failures of converters in any level.

**Gradual Degradation**

If the system having 5 converters in series and 3 branches in parallel (5 s - 3 p system) incorporates a module concept, wherein 5-series converters form one module that is assembled on one common heat block such as a heat pipe, an allowable range of the temperature variation of one module has to be examined to establish the design criteria for, say, the heat pipes. Temperature variations may occur in emitter temperatures, collector temperatures, and cesium reservoir temperatures as well. The effect of collector temperatures was not considered since it is usually small. The temperature variations of emitters and cesium reservoirs were considered separately although they may occur simultaneously.

First, the volt-ampere characteristics of a thermionic converter such as are shown in Fig. 4 are linearized. The curves were obtained from a research converter having a rhenium emitter and a molybdenum collector with an interelectrode gap of 0.010 inch. The parameters of the linearized converter depend on temperatures as shown in Figs. 5 and 6. If the cesium temperature can be optimized each time the emitter temperature change occurs, the reduction of the open circuit voltage of a converter is approximately 0.15 volts/100°F, whereas the internal resistance of the converter remains almost unchanged. Therefore, the emitter temperature change appears as the change in the open-circuit voltage $E$ of an individual converter in the system. Let $E$ be reduced to $\gamma E$ ($\gamma < 1$) for 5 converters in a module because of lowering of the temperature of a common heating block for 5 converters in series. Then the output power available from the 5 s - 3 p system that was $15 E^2/4 R$ initially reduced to $5(2 + \gamma)E^2/12 R$. For the allowable reduced power to be 83% (the available power in case of an abrupt failure was also 83%), $\gamma$ must be 0.782. Therefore, the reduction of 150°F in emitter temperatures is allowable in this system, whereas the lowering of just 25°F in the emitter temperature will cause the same reduction in power output for a single converter system.

Variations of cesium reservoir temperatures cause variations of the open-circuit voltage as well as the internal resistance of the converter. However, the changes in open-circuit voltages due to changes in cesium temperatures do not cause an
Fig. 4. Typical volt-ampere curves for a thermionic converter.

Fig. 5. Temperature dependence of the parameters of a linearized converter.

appreciable change in the system power output compared with that due to changes in the internal resistance of converters. Let an equivalent internal resistance of a converter become $R$ due to a change in cesium reservoir temperature, and let all 5 diodes that are connected in series be subjected to similar changes. Then, the equivalent internal resistance of the generator system becomes $5R/(1 + 2\beta)$. If the available power is allowed to become 85% of the nominal value, $5R/(1 + 2\beta)$ can be made equal to $5R/3$ (the original internal resistance at $\beta = 1$) times $1/0.86$, since the available power is inversely proportional to the equivalent internal resistance of the generator. Therefore, $\beta$ can be as large as 1.72 for the available power to become 85% of the nominal value. In other words, the internal resistance $R$ of the individual converter can be 1.72 $R$. An increase of this magnitude would occur when the cesium reservoir temperatures of 5 diodes in series reduces 15$^\circ$K from a near-normal value of 610$^\circ$K. In contrast, only 2 to 3$^\circ$K of change would reduce the available power output to 80% if the system had only one converter.

It is therefore obvious that the multiconverter generator system is considerably superior to a monoconverter system with respect to temperature controls to maintain a satisfactory power output.

System Reliability

Users of electrical power have to know the confidence level at which a required power is available from the power package. To achieve a high reliability, multiple elements with high reliability must be assembled into a system.

In this study, the reliability of a particular thermionic generator system was investigated for different modes of failures. A generator system that was selected for the study was composed of 15 converters. The converters were connected in series to form a branch and then these branches were connected in parallel with interconnecting resistances, each of which was equal to 3 times the internal resistance of the converter. Interconnections were in 4-circuits in order to form a symmetrical three-dimensional array that had less edge effect than two-dimensional arrays. Because of symmetry, the probability of failures could be calculated with relative ease. For a failure of a single converter in a 5 a - 3 p network, only three different probabilities
Fig. 6. Temperature dependence of the power density of a linearized converter.

The reliability $Q$ of the system is defined as the probability at which a power output better than or equal to a certain level can be achieved. Therefore, the reliability is a function of the output power of the system. We further define the performance index $P$ as the integral of the relative power with respect to the reliability number for a given system. The performance index can also be calculated for power output that is available after the power conditioning; in this case the efficiency of the power conditioner (which is influenced by the output parameters of the generator system) will be reflected in the index. The closer the performance index to unity, the greater the inherent reliability of the generator network.

To calculate the reliability, the probability of an occurrence of a certain failure mode that results in a certain available power output was first found. For example, in the 5 s - 3 p system when the first open-circuit failure occurs in one of the three converters in the first level and the second open-circuit failure in another converter of the remaining two converters in the same (first) level, the available power becomes 0.607 of the nominal value. The probability for this type of failure to occur equals

$$2 \times \left\{ 3 \times (1 - p)^{\frac{11}{13}} \right\} \times \left\{ 2 \times (1 - p)^{\frac{13}{13}} \right\}$$

where $1 - p$ is the reliability of an individual converter. The reliability $1 - p$ is equal to the percentage of converters which would survive a given mission without failure. Therefore, a probability for two such consecutive open-circuit failures to occur would be 0.0076 for converters with 95% reliability ($p = 0.05$). Similar calculations have to be repeated for all failures that give available power less than 0.607. Then the cumulative probability that the system fails to meet the minimum available power of 0.607 would equal the sum of all such probabilities. Hence, the reliability for the available power of 0.607 is the complement of the probability just calculated. In general

$$Q(W) = 1 - \Sigma \left[ \text{all probabilities that yield power degradation larger than } (1 - W) \right]$$

where $W$ is the relative power level ($W = 1$ for nominal power output). Failures of a higher order than two consecutive failures are neglected since the probability diminishes quite rapidly as the order increases because the probability is a product of probabilities of each failure contained in the resultant failure. A calculation of probabilities as a product implies, of course, that the failures occur independently. In reality, however, the first failure would modify the reliability of remaining converters and of their failure rates.

The reliability of the 5 s - 3 p system with $R_1 = 3 R$ is calculated for open-circuit failures only, or for short-circuit failures only. The results are shown in Fig. 7. Note that the curves are
approximately the same for both modes of failures. The reliability would probably be unchanged if mixed failures (open-circuit and short-circuit failures) are allowed to occur as they would in practical systems. The results indicate that the most probable value of available power of this particular system is approximately 0.86 of the nominal value. The most probable power was determined as the power at which the slope of the reliability $\frac{dR}{dW}$ is the maximum. However, a better reliability value of 0.99 is attained at a lower power of 0.6. Therefore, the system must be over-designed with a contingency factor of 2 for the reliability to be better than 0.99 with the nominal output of 1.0. The performance index that equals the area under the curve is 0.91 for this system. Shown in Fig. 8 is the reliability for

![Fig. 8. Reliability figure for a 5 s - 3 p power package, including power conditioner.](image)

the system including a certain power conditioner with reliability unity. The conditioner has decreasing conversion efficiencies as its input voltage decreases, such as is shown in Fig. 9. Results clearly indicate that the open-circuit failures are more favorable than short-circuit failures since the former result in larger input voltages for the power conditioner. The most probable power occurs at 0.8 in case of short-circuit failures, but it would be 0.82 in an actual system where intermixed failures occur. The performance index is 0.90 when a power conditioner is included in the consideration.

System Efficiency

The efficiency of a generator package is a product of the efficiency of the generator system and that of the power conditioner. The efficiency of the generator system that is composed

![Fig. 9. Efficiency of a dc-dc power conditioner as a function of input voltage.](image)

of multiple thermionic energy converters equals the efficiency of the individual converters that are assumed to be all identical. The efficiency of a converter becomes smaller as dimensions of the converter decrease because there are fixed edge or end losses due to heat conduction and radiation that are independent of the emitter size itself. Thus, converters with smaller nominal power output having smaller emitter areas must pay relatively large penalties due to such edge or end losses. Figure 10 is based on efficiency-versus-size calculations using a plausible edge loss model. As seen in Fig. 10, the efficiency decreases rapidly for converters with their nominal power output smaller than 20 watts. These results were obtained for planar thermionic converters, although in a system utilizing heat pipes cylindrical converters would be more suitable.

From Fig. 10, the efficiency of thermionic converters with power output of 20 watts is approximately 9% and the output voltage of the 5 s - 3 p system is 2.5 volts. The power conditioner has an efficiency of 87% at 2.5 volts input. Therefore, an over-all efficiency of the generator package will be 7.8%. If the generator system is over-designed with a contingency factor of 2 to increase the reliability, the inherent converter efficiency will increase. There are, however, other system implications involved, of heat-source over-design, and/or of off-design operation, which have to be considered. To study these, definite design concepts are necessary.

Conclusions

An electric power-generator system for space
application is examined for its power output, configuration, reliability, and efficiency.

For a system that is capable of supplying electrical power of 300 watts, a system of 15 converters connected to form a three-dimensional array seems satisfactory. Each converter has a nominal power of 40 watts (contingency factor = 2), and 5 such converters are connected in series so as to produce an output voltage of 2.5 volts. Each of the three branches may be fabricated into a module that has 5 converters mounted on one heat pipe. Three branches are then parallel-connected to form a Δ-connected cage. The Δ-connections are provided at each level of 5-series converters. The optimized resistance of these interconnections is three times the internal resistance of the individual converter. The operating temperatures of converters are estimated to be 1900°K for emitters and 610°K for cesium reservoirs. The power density per converter will be 7.5 watts/cm² with an efficiency of 9%. The over-all efficiency of the generator package including the power conditioner is 7.8%.

The reliability of the system that is composed of diodes with a component reliability of 0.95 is 0.99 with the nominal output power of 300 watts. The temperature control required to maintain the level of power output is considerably simpler compared with that which would be required for a monopower converter generator system. If the component reliability is 0.99, the required contingency factor in the design of the system will be 1.25 instead of 2 to achieve the same system reliability of 0.99.

The newly defined quantity "performance index" is 0.91 for a system of 15 converters with a component reliability of 0.95. The performance index should be quite useful for comparing performances between various systems since it reflects the inherent system reliability and the effects of component interrelationships on system output power and efficiency.

Acknowledgment

The authors are grateful to Miss Margaret Brandenberg for her assistance in the preparation of the manuscript.

References

* This paper presents the results of one phase of research performed at the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration, under Contract No. NAS 7-100.

† We define "contingency factor" as the number that multiplies the nominal power output of a generator system so that the designed system will yield nominal power with a certain reliability (0.99 in this paper). Unless the generator system is over-designed in this manner, the achievable reliability will fall short of the prescribed value because of possible converter failures.
