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A Study on the Reliability of Thermoelectric Couple Networks

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Thermoelectric generators (TEGs) rely on a network of individual thermoelectric couples that collectively contribute to the overall power output of the system. As individual couples experience catastrophic failure, complete generator failure occurs when the power output fails to meet the required threshold. A series–parallel wiring arrangement accommodates failure of individual couples without catastrophic failure of the generator, however there exist failure paths that interrupt electrical continuity of the network. In assessing the reliability of a TEG system, the probability of success is measured according to a network's ability to meet both the power level and electrical continuity criteria. A closed-form probabilistic model based on Karr's mathematical formulation (Karr in IEEE Trans Reliab 19(3):116–119, 1970) is used to assess the implications of catastrophic thermoelectric couple failure on the reliability of a complete network. A system-level analysis is performed to evaluate the reliability effects of various network configurations, based on the distribution of a finite number of couples across different numbers of strings. The study explores the tradeoff between redundancy and reliability by assessing the effect of additional couples added to parallel strings and continuing to satisfy acceptable power margins. This model is shown to be a useful tool for designing and understanding the electrical network wiring configurations of TEGs and other power devices.

Key words: Systems engineering, reliability, thermoelectrics, RTG, TEG

INTRODUCTION

Thermoelectric generators (TEGs) have been used for decades to provide solid-state power generation for a variety of applications. A TEG is composed of a collection of thermoelectric (TE) couples that are strategically wired in a network to supply power at a particular output level and reliability. A dependable power source is critical to the operability of any given spacecraft or terrestrial system (or mission), making high reliability an essential characteristic in the implementation of a TEG. Series–parallel circuitry has been commonly used as a strategy to attain high reliability in a thermoelectric network, and it is important to understand the impact of strategically designing the series–parallel network configuration. The work herein aims to investigate through numerical modeling the nature of reliability as it relates to thermoelectric network architecture.

This investigation uses Karr's[1] mathematical model to assess the reliability of a network containing W strings of L couples configured in a series–parallel wiring arrangement, as depicted in Fig. 1. There are a number of constraints to the practical application of this model. Power degradation of the TE couples compared to beginning-of-life power is not a direct consideration of this model, but can be used to assess the network reliability at a particular point in time. Implementation of this model applies exclusively to catastrophic failure, resulting in an interruption of the electrical connection at the TE couple-level. Hardware design is therefore a key consideration in establishing the inputs to the

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model. In the case of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) developed for use by NASA, the thermoelectric module design employed the use of spring-loaded compression hardware to secure the modules in place and facilitate effective heat conduction through the generator components.[2] In a spring-loaded module design, there is a low likelihood of catastrophic failure because electrical continuity tends to be mechanically maintained by the compression of the thermoelectric components. Other RTG designs, such as the General-Purpose Heat Source RTG (GPHS-RTG) used on several NASA missions including Cassini, New Horizons, and Ulysses, employed a cantilevered design for its thermoelectric assembly. In the case of mechanical failure of a cantilevered TE couple, the electrical circuit may more commonly be broken. The proposed Next-Generation RTG currently under development by the NASA RPS Program plans to utilize a cantilevered TE couple architecture, so it is critical to understand this topic in order to best design a reliable power system for future NASA missions.

Other physical effects due to aging or material degradation are not considered in this model, as this study assesses reliability related exclusively to catastrophic failure. A uniform couple reliability is applied to each TE couple in the network as an approximation. Catastrophic failure of a couple will result in an increased current level for other couples within the same series grouping (i.e. wired in parallel to the failed couple). It is not expected that an increase in current to an individual couple will lower its reliability, as defined by this model. An increase in current will lead to a Peltier cooling effect, which is not likely to increase the probability for catastrophic failure. TE couple failure is characterized by this model as a break in the electrical continuity at the couple location, which may be the result of manufacturing issues or cracking due to thermal cycling or other effects.

The model applies two requirements for success, in which the reliability measurement characterizes the probability of a network meeting both criteria. These success criteria are identified as follows:

1. Maintenance of electrical continuity throughout the circuit.
2. Sufficient number of operable couples in the network to meet the power output requirement.

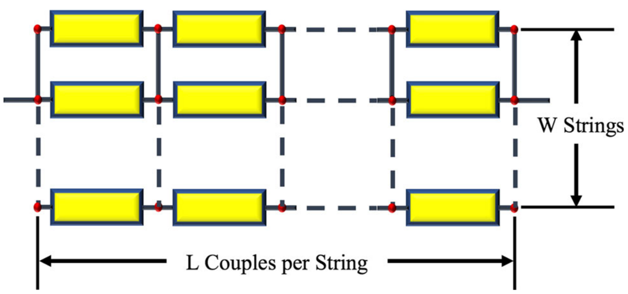

Fig. 1. Network architecture.

The first requirement for success necessitates a pathway for the circuit to be complete. As individual TE couples fail, there exists the possibility that an entire series group of couples fails, resulting in a failure pattern as illustrated in Fig. 2. The failure pattern produces an interruption in the electrical continuity of the circuit and violates the success requirement.

The second criterion necessitates that a minimum number of total couples are operating within the network in order to meet the required power output. This condition is independent of considerations relating to continuity of the circuit. This consideration may be pertinent when assessing the reliability of a TEG over its design life. The margin between the TEG's power output and the specified power requirement determines the number of allowable couple failures before violating the requirement. As the TE couples experience performance degradation over time, that margin decreases and results in fewer allowable couple failures before the power threshold is reached (see Fig. 3). If the power output generated by the total number of operable couples in a network is exceeded by the power requirement, then this success criterion is violated and the network reliability is zero.

The study presented herein is intended to be a system-level exploration to support applications of thermoelectric technology. Network design is one of a number of considerations that contribute to the design of any thermoelectric system, and this reliability model is a valuable tool that serves to characterize and assess the associated variables. Implementers of thermoelectric technology will find great value in approaching system-level studies with the information provided by this model.

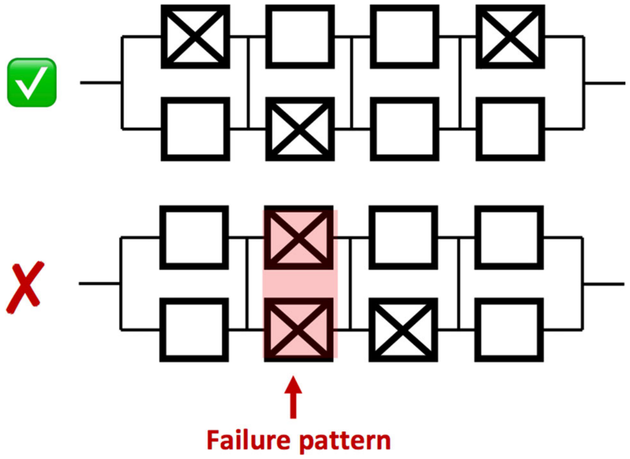

Fig. 2. Illustration of the electrical continuity requirement in a 2 × 4 series–parallel network. When an entire series group fails, a failure pattern interrupts electrical continuity.

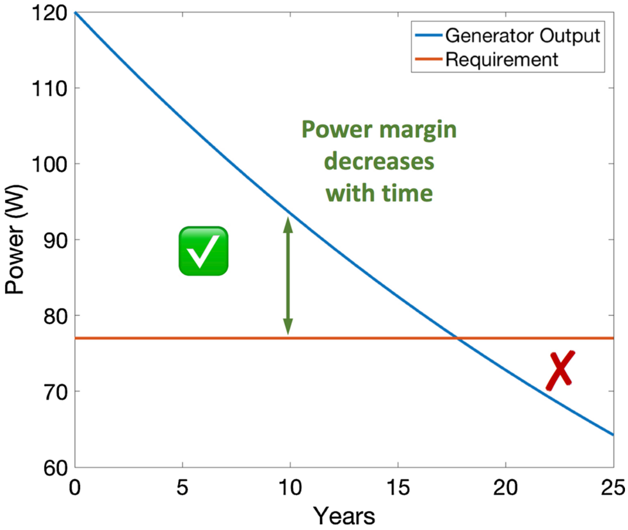

Fig. 3. The power margin of a TEG may decrease with time. The margin at any particular point in time will dictate the number of couples that may fail while still meeting the power output requirement.

SYSTEM RELIABILITY MODEL OVERVIEW

The probabilistic model used for this numerical study is based on the formulation developed by Karr.[1] This reliability assessment begins with evaluating the maximum number of allowable failures while still meeting the power requirement (i.e. the second success criterion). This value is denoted as j and calculated as the power margin divided by the power output per couple:

$$j = \frac{(\text{Power output} - \text{Power requirement})}{(\text{Power output per couple})} \tag{1}$$

The model is a binomial distribution problem, which describes the probability of having j or fewer failures, minus the probability of experiencing a failure pattern (i.e. the first success criterion). The generator reliability R_G is expressed as follows:

$$R_\mathrm{G} = \sum_{i=0}^{j} \left[\binom{m}{i} - F_i \right] R_\mathrm{c}^{m-i} [1 - R_\mathrm{c}]^i. \tag{2}$$

Here, m is the total number of couples in the network, determined by the product of the number of strings, W, and the number of couples per string, L. The term $\binom{m}{i}$ is simply the binomial coefficient corresponding to the number of combinations involving i couple failures within a generator containing m total couples. However, the actual number of couple failure combinations that may occur without preventing the generator from satisfying its design requirements for power, given that i couples have failed, is less than $\binom{m}{i}$ because of the potential for experiencing a failure pattern. In the expression, F is the term that assesses the probability of experiencing a failure pattern. This term can be solved through a Monte-Carlo analysis, but instead a closed-form solution was developed for the modeling efforts herein. It can be seen by the expression that the generator reliability is very much dependent on the couple reliability. R_c can be expressed as a standard survival function, with t representing time:

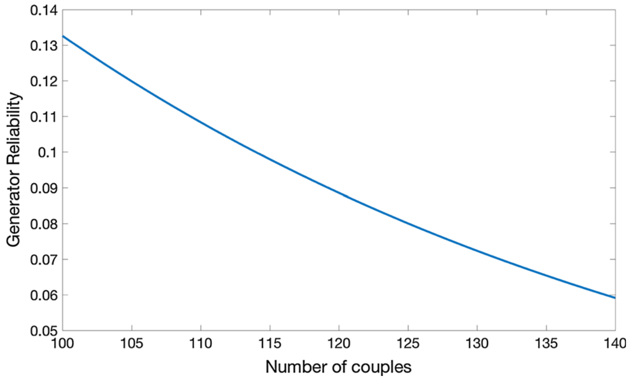

Fig. 4. Reliability of a series string of couples.

$$R_\mathrm{c} = e^{-\lambda t}. \tag{3}$$

The failure rate λ is expressed as the inverse of the mean time between failures (MTBF):

$$\lambda = \frac{1}{\mathrm{MTBF}}. \tag{4}$$

The couple reliability provides an assessment of the probability of achieving successful couple operation at any particular point in time. This quantity is applied uniformly to all couples in the network. As such, it is not expected that couple failure will have a significant impact on adjacent or nearby couples in the network. Operable couples in the same group as a failed couple will experience a proportional increase in current, which will result in Peltier cooling across those couples. Typically, it can be expected that cooling will not have a negative impact on the reliability of a couple, so the assumption of uniform reliability may be considered conservative in this case.

NUMERICAL ANALYSIS

Sensitivity studies related to network architecture and couple reliability values were employed in order to better understand the reliability behavior of a series–parallel wiring configuration. For a network containing a certain number of couples, it is expected that the reliability will be affected by configuring those couples into multiple series–parallel strings versus a single string. Furthermore, as couples are added to the network such that redundancy leads to an improved power margin, the reliability behavior of the network can be observed. Figure 4 shows the reliability predicted by the model for a single series string of couples, with an applied uniform couple reliability of 0.98. The power requirement in this example was arbitrarily chosen to necessitate 100 operable couples. This arrangement results in an unsurprisingly low reliability, as a single failure will result in complete network failure. As couples are added to the string, the likelihood of experiencing a failure increases, which negatively impacts network reliability despite an expanded power margin attributed to additional couples.

By reconfiguring the network to contain multiple strings, it can be seen that a series–parallel network arrangement has a significant reliability effect. Figure 5 displays the generator reliabilities of networks possessing one, two, and three strings (i.e. $w = 1, 2, 3$), as the strings are increased in length. A uniform couple reliability is applied here as $R_c = 0.95$. The power requirement was again chosen to necessitate a minimum of 100 operable couples in the network. Consequently, for a network containing this minimum quantity of couples, all configurations show a generator reliability of 0.0059, such that a single failure will violate the second success criterion and produce network failure. As the network size is increased by adding couples to the strings, the series–parallel arrangements (i.e. $w = 2$ and $w = 3$) exhibit different behaviors than the single series arrangement (i.e. $w = 1$), which decreases with additional network couples, corresponding to the behavior shown in Fig. 4. As couples are added to the series–parallel network above the minimum requirement of 100 operable couples, the margin between the network power output and the power requirement increases. That is, couple redundancy leads to greater protection against violating the second success criterion. For the series–parallel arrangements, the result of this increased margin is a correspondingly improved generator reliability. It can be seen that as network size increases above the minimum 100 couples, the generator reliability reaches a peak rapidly, then slowly decreases as more couples are added. The generator reliability begins to diminish at the point where the probability of experiencing a failure pattern overtakes the reliability improvement from the expanded power margin. By comparing the two and three string configurations, it can be seen that with three strings, the reliability decline beyond the peak is less rapid and barely noticeable. This result demonstrates that a higher number of series–parallel strings enables couple redundancy to be utilized with less negative impact on generator reliability.

A major consideration here is the voltage requirement of a system. The voltage output of a TE network is dependent to the length of the strings. If a network of a fixed number of couples is reconfigured into a greater number of strings, the voltage output will proportionally decrease. As the number of couples in the network is increased by extending the length of the strings, voltage will increase, but reliability will decline beyond the peak. If a greater number of strings is used, this reliability penalty may not be as much of a consideration, but the ability to add couples to the network may be limited by cost and mass constraints for the generator. Therefore, a design trade exists between voltage output, power output, cost, mass, and reliability when designing a TE network in this way.

A second sensitivity study was performed to evaluate the effect of couple reliability on overall generator reliability. This analysis assumed a 2-string, series–parallel network. Generator reliability peaks at higher and higher values as couple reliability approaches 0.995 in Fig. 6. Beyond the peak, generator reliability incrementally decreases as more couples are added to the circuit. Generator reliability, R_G, is very sensitive to thermoelectric couple reliability, R_c, even though this sensitivity analysis assumed a generator design that incorporates a 2-string, series–parallel network of couples. Figure 6 also highlights the fact that generator reliability is not highly sensitive to the number of couples once couple reliability exceeds 0.97.

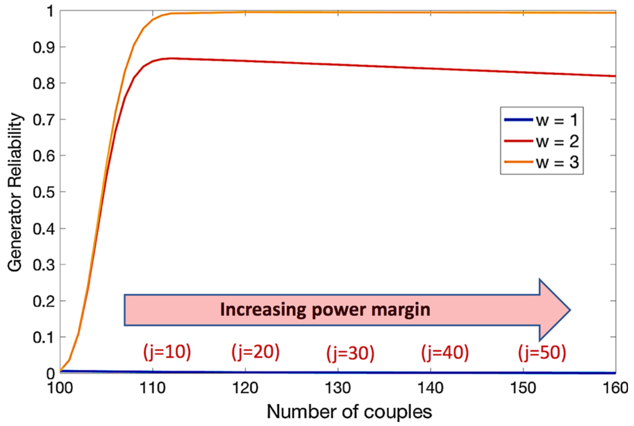

Fig. 5. Reliability of series–parallel couple networks.

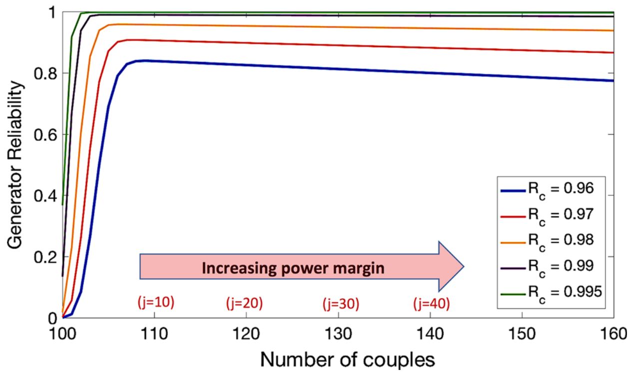

Fig. 6. Reliability of a 2-string series–parallel network with various couple reliabilities.

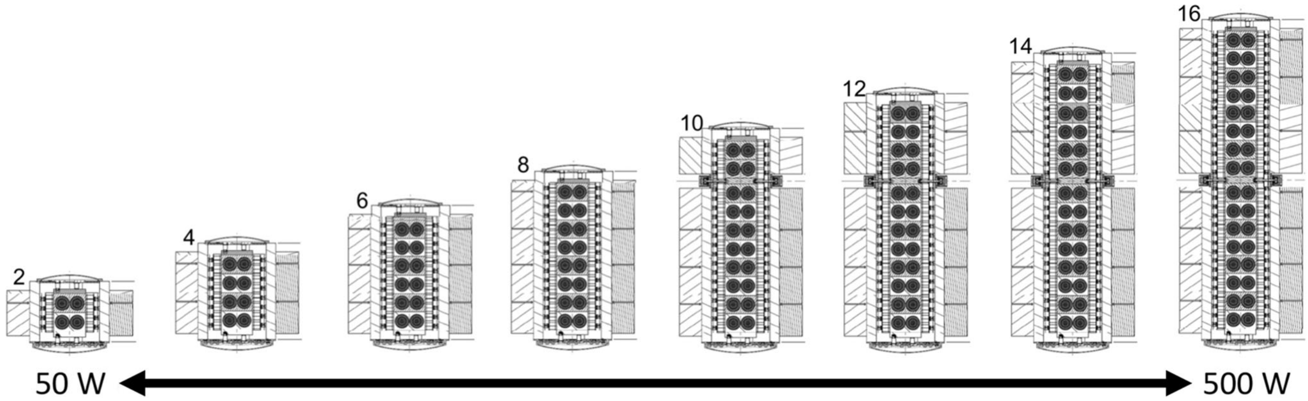

Fig. 7. Artist concept of NG-RTG system variants, power output ranging from 50 W to 500 W.

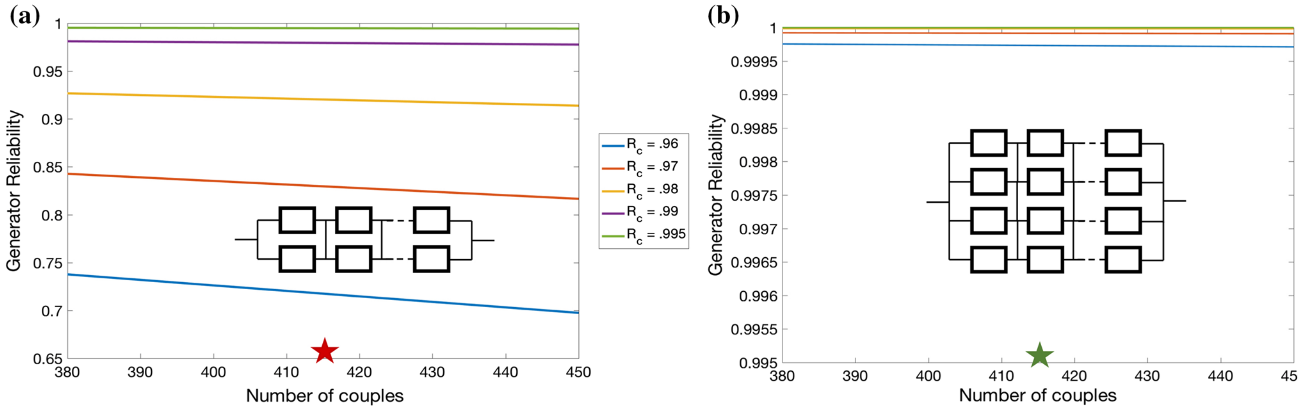

Fig. 8. Generator reliability for different couple reliabilities for (a) 2-string and (b) 4-string configurations.

RTGs typically have design lifetimes near 20 years and rely upon a 2-string, series–parallel network. Couple reliability for these generators has been very high in the past. However, generator or TEG designers can significantly offset “low” couple reliability by adding strings of couples into their electrical network. The next section expands on this observation using an example.

The NASA Jet Propulsion Laboratory (JPL) is currently investigating and developing conceptual Next-Generation RTG (NG-RTG) designs for future potential NASA missions. JPL is assessing the NG-RTG system reliability of various design options using the mathematical reliability formulation described above. The design is expected to be modular, as illustrated by the artist’s concept of the size variants shown in Fig. 7.

Each variant is defined by the number of GPHS units it contains and is a concatenation of the smallest (2-GPHS) variant, meaning multiples of that basic network are wired in parallel to maintain consistent voltage output for all size variants. Currently, the basic network for the minimal variant 2-GPHS system configuration in Fig. 7 has the capacity for 416 total couples to achieve a targeted voltage output of 34 Vdc. Figure 8 shows two possible electrical network configurations for this 2-GPHS configuration; the two subfigures each represent a different series–parallel electrical network configuration of the 416 couples.

The reliability model described herein demonstrates a key system tradeoff between generator-level reliability and the targeted output voltage. Figure 8a shows that a dual-string electrical network arrangement (i.e., 2-parallel electrical strings) for the NG-RTG design creates a significant, undesirable impact on the generator reliability from variability in the couple reliability. Generator reliability is impacted substantially when the couple reliability is lower by even a modest amount; R_c of 0.96 results in R_G less than 0.75, which is an unacceptably low generator reliability level for mission planners and designers. With a system reliability this low, the NG-RTG would not be considered as a viable power source option for future missions. There are two options for improving R_G in this case: (1) improving R_c, which may be very costly or even unattainable with current anticipated multicouple technologies, or (2) strategically re-configuring the network to make the generator reliability much less dependent on the actual couple reliability, R_c. The right-hand side plot of Fig. 8b shows the resulting generator reliability from a rather simple electrical network rearrangement to a quad-string electrical network, whereby the NG-RTG employs a basic 4-parallel-series-string configuration rather than the dual-string approach. This design modification not only significantly increases the generator reliability, R_G, but also makes the generator reliability rather insensitive to the actual value of the couple reliability, R_c. The generator reliability is demonstrated to be very close to 1 with this quad-string electrical network for a wide range of number of couples. However, the generator design tradeoff is that generator voltage output is cut in half by making this electrical network arrangement for the same number of couples as in the dual-string network configuration. Therefore, in order to regain the desired 34-Vdc voltage level, the smallest NG-RTG system variant in Fig. 7 must be a 4-GPHS generator configuration using the quad-string electrical network. This NG-RTG system reliability–voltage tradeoff has strong impact on the NG-RTG system and multicouple converter design for future NASA missions, and the generator reliability model described and exemplified herein is a critical analytic tool in that design process.

CONCLUSIONS

This study has provided insight into the reliability characteristics of series–parallel electrical networks and what design choices must be made when developing a TEG system. Distributing couples in a network to a greater number of series–parallel strings has been shown to improve the overall generator reliability and lead to a lower marginal difference in the effect of couple reliability. As such, this strategy relaxes the couple reliability requirement dramatically.

For a series–parallel network, adding couples above minimum requirement to the strings initially increases the reliability to a peak rapidly, then gradually lowers the reliability with additional couples. This behavior demonstrates the redundancy does not necessarily result in greater generator reliability, so power margin must be traded with reliability needs. Greater couple reliability results in less penalty to the network reliability for each additional couple, as is the case when the network is reconfigured to have more strings. Design trades must be performed between voltage and reliability, as well as cost and mass when designing a TE network for a generator in order to determine the most advantageous solution. The reliability-voltage tradeoff can affect the high-level design choice of minimum system size variant in meeting overall RTG system requirements.

In general, high generator reliability requires either very high couple reliability or strategic electrical network configuration. Improving the couple reliability may not always be possible, so it is important to consider the most effective means for maximizing power relative to the system needs when designing a TE network.

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