Risk Reduction for the System Design of an Enhanced MMRTG

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Engineering of an enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) began 3 years ago with agreement between the U.S. National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy (DOE). The Jet Propulsion Laboratory is leading the transfer of skutterudite thermoelectric couple technology to industry and leading the systems engineering of the proposed eMMRTG. Should NASA fund the flight development of an eMMRTG, the DOE would lead the flight system development. The analytical models and design of the MMRTG have been enhanced to use skutterudite couples developed at Jet Propulsion Laboratory over the last two decades. This required a thorough evaluation of the MMRTG design, and concurrent engineering of an enhanced MMRTG to shed light on potential design issues or risks. At the end of the U.S. fiscal year (FY) 2015, a complete catalog of risks was produced. Tests, hardware development, and analyses have now been put in place to mitigate those risks to acceptable levels. Few risks can ever be truly eliminated unless a design is modified to eliminate specific risks and not introduce more severe risks. The design imperative for the eMMRTG is to change only a few MMRTG features; therefore,

risks can largely only be mitigated, not eliminated,through design changes. However, many risks can be effectively—though not totally—eliminated without design changes. This paper briefly describes some of the documented risks and mitigations or reduction approaches to be applied in the coming 3 years, on the way to completing the eMMRTG concept.

Key Words: eMMRTG, radioisotope thermoelectric generator, risk mitigation, risk reduction, skutterudite, spacecraft power.

INTRODUCTION

Engineering of a proposed enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) began 3 years ago with agreement between the U.S. National Aeronautics and Space Administration (NASA) and the U.S. Department of Energy (DOE) [1]. The Jet Propulsion Laboratory is leading the transfer of skutterudite (SKD) thermoelectric couple technology to industry and leading the systems engineering of the eMMRTG at this time. Both efforts use risk management.

NASA has used quantitative risk analyses for many years and makes its techniques available on the internet [2]. Work on the eMMRTG is being performed for NASA's Radioisotope Power Systems Program, and so the systems engineering of the eMMRTG falls under that Program's risk management plan [3]. The plan allows for a two-tiered approach. Risks evaluated to carry highly consequential threats and risks

whose breadth entails the technology being enhanced *and* the system design of the generator are given the most visibility. Statuses of those risks and the actions taken to reduce their threat are reported regularly to NASA management. Those risks are Program-level risks. Risks that are lesser threats *and/or* affect just the system design of the generator are reported upon less frequently, effectively, bi-annually. Those risks are System-level risks. Risks that are purely risks to the technology are beyond the scope of this paper.

The evaluation and categorization of risks for the eMMRTG requires expert judgment in many cases and a discussion of this process is beyond the scope of this paper. However, the outcome is that each Program-level risk is graphically placed on a 5 × 5 matrix whose two axes are Consequence of Occurrence and Likelihood of Occurrence (see Figure 1). Both consequence and likelihood of a risk are assigned a value between one and five, one having the least consequence or lowest likelihood of occurring and five representing a severe consequence or very high likelihood of occurring. This graphic is used to report progress in ameliorating risk and to provide a single visual that shows all Program-level risks on a single chart, as ALL Program-level risks appear within one matrix.

Figure 1 depicts the placement of 3 fictional three risks, A, B, and C; it illustrates how they evolve with time along the arrows drawn on the graphic. Risk A begins life as a risk with a consequence of 4 and likelihood of 3, or in shorthand, a 4/3 risk. With time and mitigation, risk A is converted to a risk of 2/1. Similar trajectories are

drawn for risks B and C. Note: Figure 1 is a matrix that can be used to map risks on two axes and through color coding quickly convey the severity of a risk. Risks with the greatest likelihood and greatest consequence would be placed in red cells. Risks with the lowest combination of likelihood and consequence would be placed in the green squares, and the medium risks would be placed within the yellow cells between red and green.

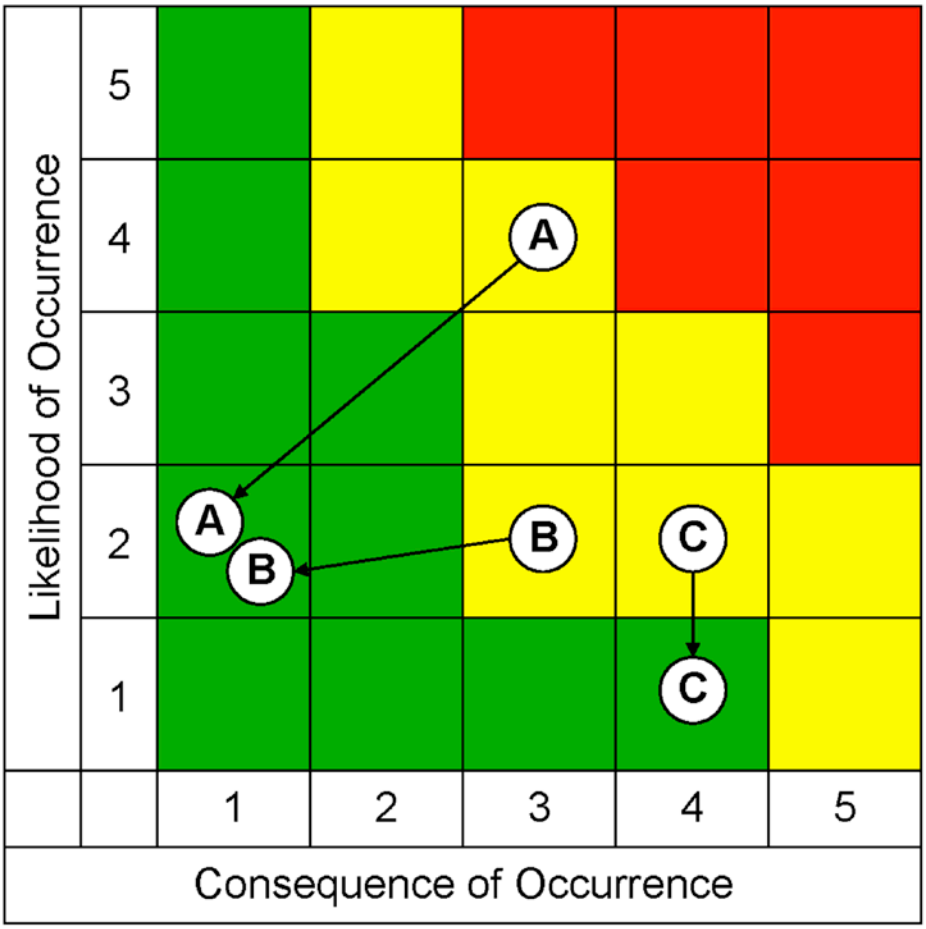

Fig. 1. A 5 × 5 risk matrix.

This paper briefly describes the risks and the mitigation or reduction approach to be applied in the coming 3 years, on the way to completing the eMMRTG technology transfer to industry, after a brief introduction to the eMMRTG concept.

THE eMMRTG

The MMRTG design has been proven flight-worthy, and the first flight unit is operating well on Mars powering the Curiosity Rover [4]. The proposed eMMRTG is an enhancement of the MMRTG. Those enhancements increase the risk of the eMMRTG over the MMRTG simply because the design would be changed from being qualified for space flight to a design needing qualification. What are those enhancements and what are the concomitant risks that have been introduced? The design of the eMMRTG concept can be found elsewhere [5], but will be briefly described here to provide context.

Figure 2 is a cutaway of the MMRTG. The generator, with eight fins, is depicted, and several key features of the generator are labeled. The planned enhancements of the generator are encircled in full-line boxes, and enhancements being considered are encircled in dashed boxes. Each enhancement spawns risks that might not be immediately obvious. The lower-most encircled item in Figure 2 is the Thermoelectric Couple Assembly. The MMRTG PbTe/TAGS (Tellurium, Antimony, Germanium, and Silver) thermoelectric couples (TECs) that operate at ~535°C would be replaced with SKD thermoelectric couples [6] that operate at ~600°C; this is not a System-level enhancement but rather a technology enhancement that *introduces* System-level risks because of the higher temperature. Above that assembly in the figure is the Microtherm Insulation. This is likely to be replaced with

a blend of Microtherm and aerogel; again this is not a System-level enhancement but rather a technology enhancement that *introduces* System-level risks because of the change in the thermal performance of the insulation and other reasons to be elaborated on below. The third and last encircled item is the Isolation Liner Assembly. The inside diameter of the liner will be oxidized to raise its emissivity. This *is* a System-level enhancement. It is being enhanced to support a higher operating temperature of 600°C and as a consequence introduces, *by itself,* risk.

The enhancements to the eMMRTG have resulted in identification of one Program-level risk and numerous System-level risks. Table I is a partial listing of those risks.

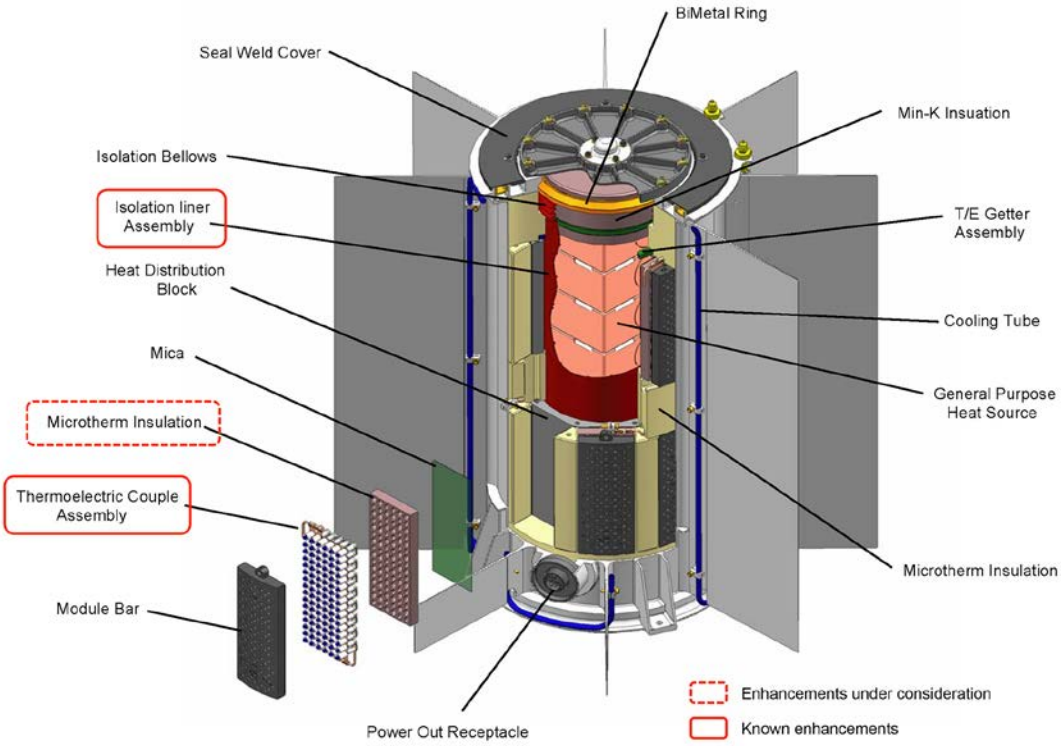

Fig. 2. Cutaway of an MMRTG with highlights on items to be modified to create an eMMRTG.

Table I. A partial list of eMMRTG System-level risks.

	Source of issue	Risk	Level
1	System environment	Deleterious reactions could occur between new TECs and gases in eMMRTG increases thermoelectric couple degradation rate beyond allowable limit.	Program
2	Liner emissivity	The new emissivity may be unstable with time and temperature and/or the change may introduce significant manufacturing issues.	System
3	Heat source support	New, higher operating temperature could weaken the heat source support	System
4	High temperature	New, higher temperature combined with current uncertainties in predicting MMRTG internal temperatures could force design changes	System
5	Qualification temperature	New upper temperature limit for qualification of the generator could impose design changes.	System

The risks listed in Table I are not in priority order and, as a subset of the complete list of risks being tracked, provide only a partial picture. The list is merely illustrative.

RISK REDUCTION FOR THE SYSTEM DESIGN OF AN ENHANCED MMRTG

For each of the risks in Table I, a statement of work to mitigate each risk has been written, and work has begun to reduce or effectively eliminate the risks. One risk might require tests; another may need analysis; still another might demand a detailed investigation, followed by development of a new generator processing approach.

Each risk will be tackled by experts whose plans are intended to retire each risk.

All of the items in Table 1 are "in work" or being mitigated. For example, for line 1, a time history of the gases the SKD TECs will be exposed to at the generator factory is being documented, and where unknown, are being sampled and assessed. This information can then be used to model the effects of the gases and vapors on the TECs. Recommendations to change the generator processing will be made where gases are assessed to be detrimental to the life of the thermoelectric couples.

For line 2, segments of the isolation liner will be tested with the newly required emissivity both at time and temperature to assess stability of the emissive layer and

manufacturability of the liner. These tests will take about a year, and will measure the stability of the layer and identify unforeseen manufacturing issues, if any.

In another example, for line 4, an exhaustive comparison of the operating limits of the MMRTG components will be compared with the predicted eMMRTG operating temperatures. Temperature margins will be documented to enable informed decisions about what temperature would be an acceptable upper limit for the eMMRTG qualification.

Figure 3 is a schedule of the remaining, planned risk reduction tasks. It has been arranged to address the highest risks first, so items listed in blue and italicized text are being worked on at this time. Those risks listed in black text will be worked on in the next 2 years. Clearly, work is spread over the next 3 years, and risk reduction is timed to finish by the end of FY18 in support of a potential decision by NASA to fund the DOE to procure flight eMMRTGs.

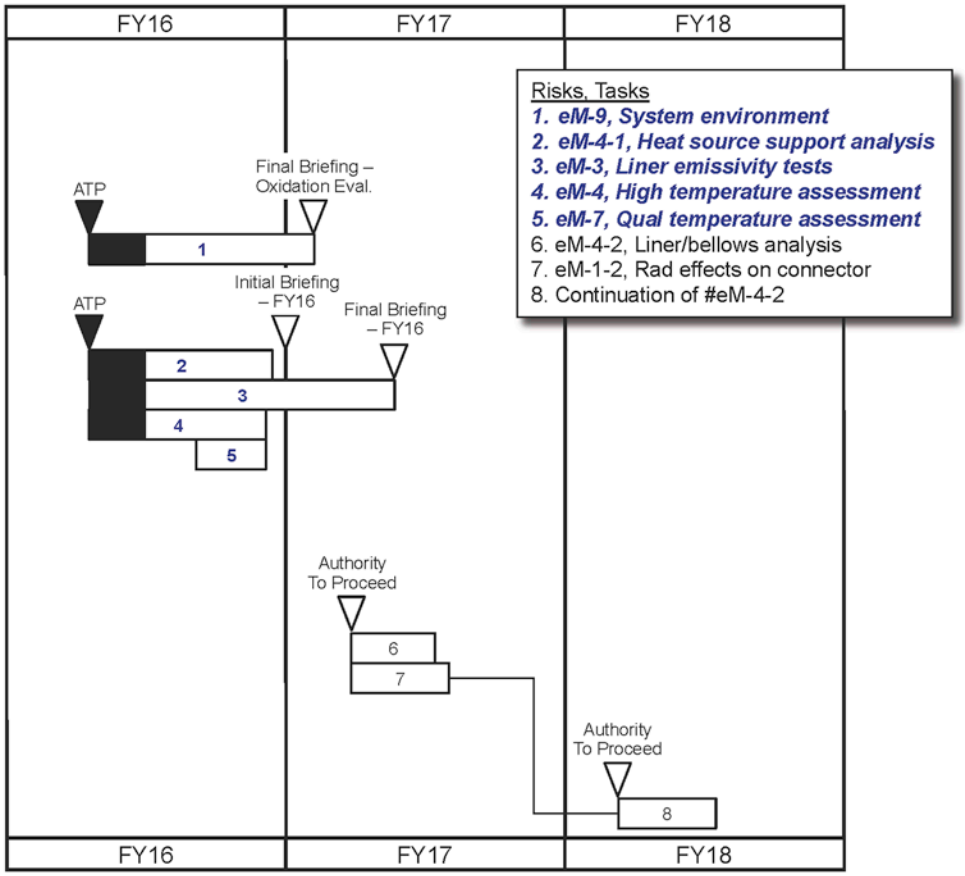

Fig. 3. Current schedule of risk reduction tasks for the eMMRTG.

Conclusion

The eMMRTG is in its third year of engineering. The concept initially envisioned in 2013 remains largely unchanged, allowing the system engineers to focus on risk reduction. Risk reduction tasks have been planned for the next 3 years to retire or effectively eliminate the risks. Successful risk reduction will provide confidence to the Radioisotope Power Systems community and give NASA's decision makers the data needed to make an informed decision to fund a flight hardware development.

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