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Structural Vibration Analysis of the Multi Mission Radioisotope Thermoelectric Generator (MMRTG) on the Martian Surface

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Abstract*—A Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is a type of radioisotope power system that is designed for use within both planetary atmospheres and the vacuum of space. A radioisotope power system utilizes a radioisotope as fuel to generate heat which is converted into electricity. These generators are used on space missions that require a long-term energy source. Because MMRTG have a required usage lifespan of roughly fourteen years without being serviced, they need to be able to withstand the stressors caused by the launch, docking, travel, and landing sequences of the spacecraft that they are being transported on. It is also extremely important to remember that MMRTGs house radioactive materials; therefore, their resilience is crucial not only to the success of the space mission, but also to the safety of the public. In order to minimize the dangers posed by these nuclear materials it is necessary to optimize the structural integrity of the MMRTG. Thus, ensuring that in the event of a mission failure wherein the MMRTG is sent into Earth's atmosphere, the nuclear material housed within the generator remains contained. For both of these reasons it is necessary to ensure the structural integrity and resilience of the MMRTG and to provide recommendations for material optimizations that can be applied to its construction. In service of this goal this paper presents a finite element analysis (FEA) of an MMRTG model subjected to various impact scenarios. An analysis of the MMRTG's structural integrity under gravitational loads will be performed along with a direct drop impact test and a vibrational analysis with the purpose of simulating those shocks that the MMRTG would experience while traversing Martian terrain via Mars rover. Using COMSOL Multiphysics, a comprehensive 3D model was developed, incorporating boundary conditions and material properties appropriate for simulating impact environments. Data on PSD estimation for terrain simulation, construction dimensions, and material properties was gathered via publicly available documents from various sources including the United States Department of Defense (DoD) and The National Aeronautics and Space Administration (NASA). By utilizing this information this study aims to understand the structural integrity and resilience of MMRTGs under relevant conditions, with a focus on time-dependent shock load application and structural response.

***Keywords*—MMRTG, Shock and Vibrations, Perseverance Rover, Impact Loading GPHS**

I. INTRODUCTION

A. Context and Importance

MMRTGs are essential for providing long-term power in space missions, particularly on planets with limited solar energy, such as Mars [1]. As critical power systems, these units must withstand various impact forces during launch, landing, and operation on extraterrestrial terrains. The MMRTG faces the greatest risk of damage during takeoff and orbital reentry. The entire spacecraft experiences great vibrational forces during takeoff. Additionally, if the launch of the spacecraft is aborted then the MMRTG can become dislodged from the rest of the components in the aftermath. In this case the risk of valuable radioactive materials being lost is high. For this reason, it is imperative that the MMRTG system has the structural integrity to remain intact so that its radioactive fuel can be properly recovered afterwards. Forces experienced during the later stages of a space mission If these forces are equally dangerous, not just to the MMRTG but to the space mission itself. If the MMRTG is unable to withstand the chock forces produced during extraterrestrial use, then the mission runs the risk of losing its main power source. This could lead to the mission needing to be aborted. If the various forces an MMRTG will encounter are not accounted for properly in its design, then they could damage or destroy the equipment.
Additionally, there is the risk to public safety that a compromised MMRTG presents. Because MMRTGs contain radioactive materials, their structural integrity is critical not just for the space mission, but also for the safety and wellbeing of the public. There have been three previous failed missions that utilized radioactive material as a power source. In the failed launch of the transit 5-BN-3 navigational satellite the plutonium fuel onboard the satellite successfully dispersed itself into the atmosphere after the generator burned away on reentry [2]. The plutonium fuel of

the nimbus B-1 weather satellite was able to be recovered and reused in later missions. However, the most recent incident occurred when the nuclear fuel source onboard the Apollo 13 mission was lost in the Pacific Ocean when the spacecraft was returning to Earth. Though this was deemed to be the design working as intended; using the ocean as a radioactive fuel disposal is irresponsible, dangerous, and poses great risk to the safety of the public. Thankfully there have been no incidents where a damaged MMRTG's fuel source causes direct harm to the public but, in order to ensure the safe use of radioactive materials continues without incident it is necessary to optimize the construction of the MMRTG.

B. Objective

The primary objective of this research is to analyze the MMRTG's response under those conditions which it is most likely to face during regular use. The system will be exposed to gravity, as well as the shock forces that would be a result of a direct drop and those dynamic loads incurred while mounted on the brackets of a Mars rover. These simulations will allow the system's response to be analyzed so that its construction can be optimized.

The analysis will utilize information gathered from the available information regarding the previous uses of the MMRTG, such as those on the Curiosity and Perseverance rovers. Documentation from these missions provides valuable information of the forces encountered during launch, entry, descent, and landing as well as vibration and shock profiles during rover traversal, which will be imperative to the dynamic load analysis. Replicating these conditions as closely as possible will identify vulnerabilities and enable the informed recommendation of design optimizations to enhance the durability and safety of future MMRTG systems.

II. LITERATURE REVIEW

A. Current MMRTG simulations within COMSOL

COMSOL Multiphysics is not typically used to simulate large and highly complex objects such as the MMRTG. Due to the intricate nature of the MMRTG and its systems, which involves a combination of electrical and thermodynamic principles, the modeling of such systems is more specialized and often requires custom solutions beyond the capabilities of COMSOL's physics modules. As a result, there is little to no available information on the specifics of using COMSOL for this purpose. In order to circumvent this limitation, the complexity of the MMRTG's model has been greatly reduced; most notably the eight GPHS modules have been modeled as a simple block primitive with equivalent density, Youngs's modulus, and modulus of elasticity. Additionally, since the MMRTG is symmetrical from the top view its model was reduced to a quarter slice to further reduce its complexity. Furthermore, thermodynamic and electrical properties will be omitted and only the structural dynamic properties of the system will be accounted for in the COMSOL simulation. A comparison can be made with the work of Liu, Zhang, Wang, and Chen in, *"Comprehensive modeling and parametric analysis of multi-mission radioisotope thermoelectric generator" [5]*. In this research, a more detailed modeling approach that integrates electrical, thermodynamic, and mechanical analyses to evaluate the MMRTG's performance was employed. This work was centered around the thermodynamic properties of the MMRTG

In contrast, the modeling and COMSOL simulation process described here was simplified to only account for the MMRTG's structural dynamics. This limitation removes the complexity of thermoelectric conversion, heat generation, and electrical performance, focusing solely on the mechanical properties of the MMRTG. While this simplification reduces computational complexity, it also limits the insight into critical thermodynamic and electrical interactions that could impact the MMRTG's performance under real-world conditions in service of purely structural optimization.

B. MMRTG Design and Space Applications

The Multi Mission Radioisotope Thermoelectric Generator (MMRTG) is a type of nuclear generator used to power the different components of a spacecraft during missions. It was most recently used as the power source of the Mars 2020 perseverance rover where it enabled the continuous operation of the rover within the harsh Martian environment. During the mission the generator was able to provide continuous 110W power with its plutonium-238 fuel source [3]. The MMRTG contains eight General Purpose Heat Source (GPHS) modules, each of which contains four Plutonium-238 fuel pellets. In order to contain the radioactive material safely and minimize heat loss; the pellets are contained within an iridium cladding which is then contained within a fine weave pierced fabric (FWPF) graphite sleeve. As the plutonium decays it releases large amounts of heat. This heat is absorbed by the GPHS, which glows red with from its heat during use. All eight of the GPHS modules are contained within a heat source liner which helps to insulate the other MMRTGs components, as well as the other spacecraft components, from the extreme temperatures. The heat source liner is in contact with each of the eight heat distribution blocks. The heat distribution blocks are made of graphite and further help to distribute the heat evenly from the GPHS modules, through the heat source liner and into the thermocouples. Each of the heat distribution blocks is attached to a thermoelectric module [5]. In total the MMRTG contains 768 thermocouples which are divided into sixteen 16 x 4 arrays. The thermocouples' cold sides are maintained by contact with the shell and cooling tubes that run along the eight aluminum fins positioned radially on the outside shell and channel the cold of space to the cold side of the thermocouple modules. The remaining empty space within the shell is filled by thermal insulation The top and bottom of the GPHS stack is insulated with Min-k while the sides and spaces between the thermoelectric modules/heat distribution blocks is insulated primarily with microtherm insulation [6]. The thermocouples themselves are made of lead tin telluride (PbSnTe), TAGS (TeAgGeSb), and lead telluride (PbTe). These materials were previously proved effective during their use in the RTG's on Nasa's Pioneer and Viking missions.

III. SHOCK AND LOAD ANALYSIS IN COMSOL

A. PSD and Random Vibration Data

In order to adequately simulate the vibrations experienced by the MMRTG during normal use, a PSD function must be implemented into the simulations. A PSD (power spectral density) is a plot that conveys how vibrational energy is distributed across different frequencies. In the context of terrain simulation, it allows the frequency-dependent vibrational characteristics of a rough surface to be quantified and used as an input force for vibrational analysis [7]. A PSD can be thought of as a function or rule that receives a frequency and outputs the corresponding force. There are many types of PSD functions, and they vary by the relationship between frequency and amplitude. White noise PSD offer a constant spectral density across all frequencies, while Lorentzian PSD has an energy peak at a given frequency with energy decaying as frequencies differ from the given value. The power-law relationship is a popular function used for PSD that is meant to simulate terrain. The power-law relationship is set up so that lower frequencies are representative of larger irregularities in the surface and thus contribute more vibrational energy than higher frequencies which represent smaller surface irregularities [8]. This function is reflected in the Department of Defense's PSD which is defined in their testing method standards MIL-STD-810G COMSOL's [10] random vibration study uses a PSD as well as vibrational input data during its operation. In this application the vibrational input data is a representation of the rough Martian terrain. This is represented as a two-dimensional plot. This plot then undergoes the Fourier transform which converts it to the frequency domain where it can be modified with the PSD. Then the system being analyzed is subjected to the PSD modified signal and its stresses are analyzed.

B. Simulation

By utilizing the commercial software COMSOL Multiphysics and its numerous Multiphysics packages the shock and impact experienced by the MMRTG can be simulated and recorded. 3 COMSOLs random vibration study utilizes a user-provided power spectral density (PSD) function applied to provide input forces in order to simulate the effects that a random vibration would have on the given system. This is the method chosen to simulate the shock and vibrational forces that an MMRTG would experience under extraterrestrial conditions. Specifically, this simulation will be based on the conditions experienced by the MMRTG on board the Mars Perseverance rover [9]. As such, the input parameters for this simulation will be gathered from the available mission data from the perseverance rover as well as other sources involved in the research of Mars. The goal of this simulation is to simulate the vibrational forces as closely as possible and generate a corresponding stress and displacement plot in order to visualize the damage that an MMRTG would experience during usage. The PSD of the input frequency of this simulation is taken from the United States Department of Defense's vibrational testing standard MIL-STD-810G METHOD 514.6 ANNEX C [10]. This document is a compilation of the testing methods recommended in order to quantify the environmental stresses that are applied to a material throughout its service life. Within it is a table of PSD values for frequencies ranging up to five hundred hertz. This table is specified to be for four composite wheeled vehicles. Since the Mars perseverance rover falls into this vehicle category the PSD given by this table will be utilized in the COMSOL random vibration simulation. The gravity and drop tests will not require as much research and configuration as the vibrational test, but they are just as crucial to understanding the shortcomings of the MMRTG. The gravity test will analyze the stresses and deformation of the MMRTG under only the force of Earth's gravity. This will allow for the establishment of a baseline of acceptable stress levels.

IV. METHODOLOGY

A. Integrating MMRTG model within COMSOL

The MMRTG was modeled in SOLDIWORKS as two separate assemblies. The GPHS assembly contained the following components: aeroshell, aeroshell cap, impact shell, GIS sleeve, fuel pellet, fuel cladding, and floating membrane. The dimensions of these materials were gathered from [11]. Once the GPHS module model was completed its Yung's modulus of elasticity as well as its Poisson's ratio was found analytically using stress and strain simulation in COMSOL Multiphysics. The density of the GPHS was calculated using the recorded weight and dimensions of the assembly [12]. These values were then applied to a box of the same dimensions as a way to accurately simulate the response of the GPHS while reducing the computation power necessary to perform complex shock simulations. The shell and fins of the MMRTG were modeled as a separate assembly using parameters outlined in [13]. The insulation, thermocouples, heat distribution block, and heat source liner were modeled as a subassembly to ensure that they fit together. The dimensions for these parts were estimated from figures and information found in [14] and [15]. The relevant material properties of these components were easily found through the same sources where the dimensions were gathered. Although, multiple values had to be estimated due to a lack of available information. For example, the Poisson's ratio and Yung's modulus values for the two types of insulations used in the MMRTG as well as the complex components of the GPHS were estimated based on the properties of similar materials. Once all components of the MMRTG were modeled the final assembly was constructed in SolidWorks and exported as a STEP file to ensure compatibility with COMSOL

V. RESULTS AND DISCUSSION

A. Simulation Parameters and Results

The MMRTG underwent a series of structural tests including drop testing and gravity load simulations. The gravity load simulations were conducted at normal gravity (1g), three times normal gravity (3g), and forty times normal gravity (40g) to evaluate the structural integrity of the system under varying gravitational conditions. The results of these simulations showed the highest stress concentrations at the connectors attaching the generator's wings to its outer shell. This finding was consistent across all gravity conditions, with stress levels increasing proportionally as gravity increased. The rest of the MMRTG experienced significantly lower stress levels, indicating that the majority of the mechanical strain was localized to the wing connectors. Displacement analysis revealed that the majority of structural deformation was concentrated on the wings, which exhibited significant displacement primarily at their top and bottom edges, indicating a very pronounced flexural response to the forces applied to the system This bending behavior suggests that the current structural design of the wings may contribute to excessive deformation underload, potentially affecting the overall stability and longevity of the system. These findings highlight a clear area where structural optimization can be implemented. Given that the connectors experience the greatest mechanical stress, reinforcing these components or redistributing the load more effectively could enhance the overall durability and resilience of the MMRTG. Further analysis, such as material optimization or alternative connector designs, will be explored in pursuit of this idea with a focus on improving the long-term performance of the MMRTG, particularly in high-gravity environments and high impact scenarios. It's also important to consider that the MMRTG is designed to withstand extreme gravitational loads but also a variety of environmental stresses that can be encountered over its operational lifespan. These include radiation, thermal cycling, vibration, and mechanical shock. While the gravity simulations offer a focused insight into gravitational stress, addressing these other factors will be essential for ensuring the overall durability and safety of the MMRTG.

Surface: von Mises stress (N/m2)

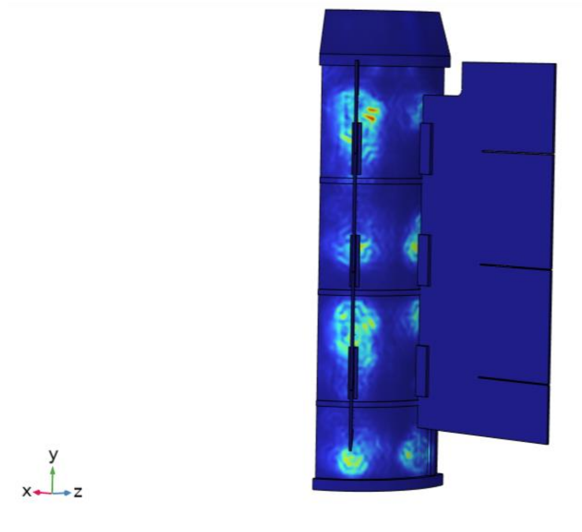

Figure 1: Drop test stress plot

Case 1: Drop Test
This case simulates the stress that would affect the MMRTG if it were dropped from a height of one meter.

Surface: von Mises stress (N/m2)

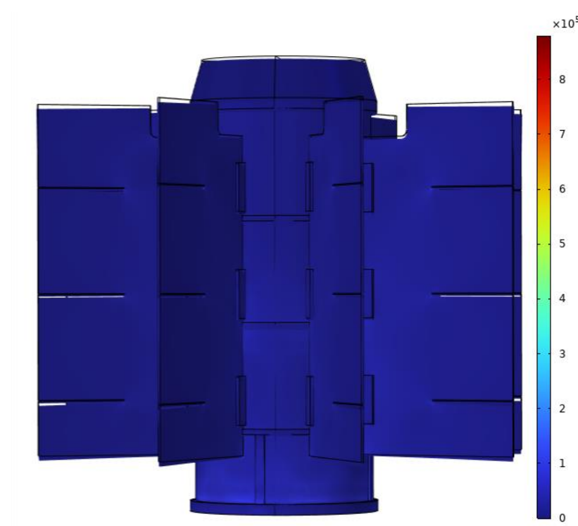

Figure 2: Stress plot under normal gravity

Case 2: Gravity Loading
This case simulates the effect of Earth's gravity on the MMRTG, providing a baseline structural analysis under static load conditions.

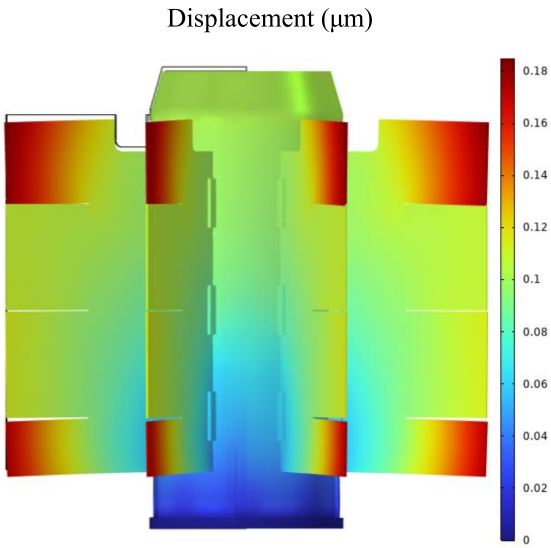

Figure 3: Displacement plot under normal gravity

Case 2: Gravity Loading
This case simulates the effect of Earth's gravity on the MMRTG, providing a baseline structural analysis under static load conditions.

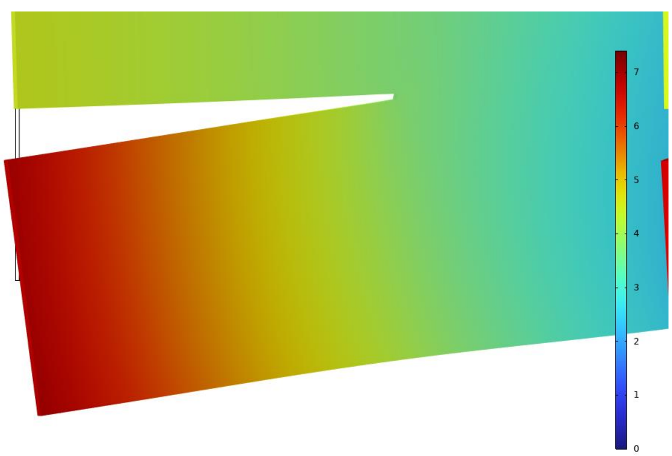

Figure 5: Zoomed in image of highest stress location.

Explanation: Significant bending occurred at the top and bottom edges of the MMRTG's wing

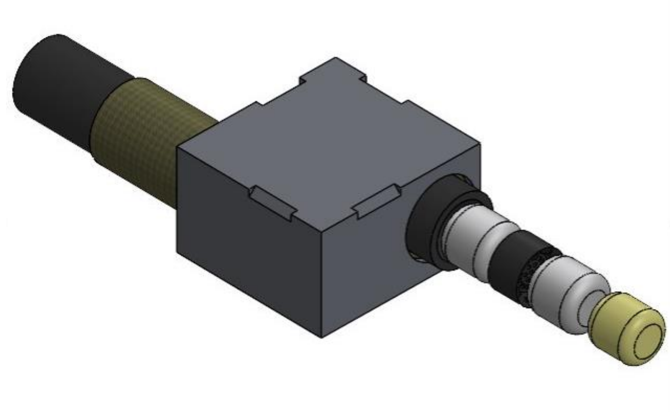

Figure 5: GPHS module assembly

Explanation: The GPHS module has six distinct parts that were each modeled separately before the final assembly was created in SOLIDWORKS. Ultimately, to reduce computational strain. The structural properties of this assembly were analyzed and applied to a solid block of the same dimensions for use in COMSOL simulations.

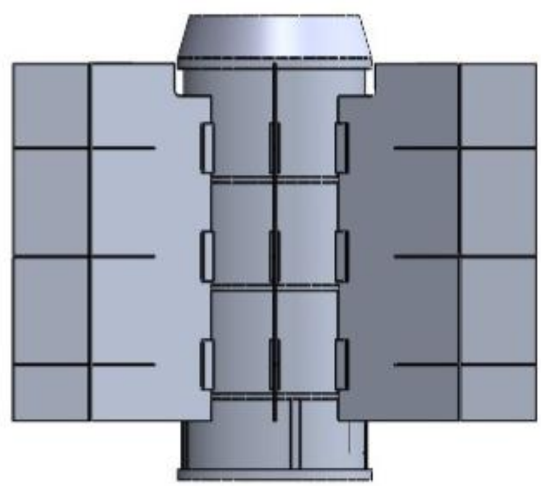

Figure 6: MMRTG assembly

Explanation: The MMRTG's shell, wings, top and insulation were each modeled as separate parts in SOLIDOWKRS. Once the separate part models were complete, they were all assembled and the final MMRTG model was imported into COMSOL.

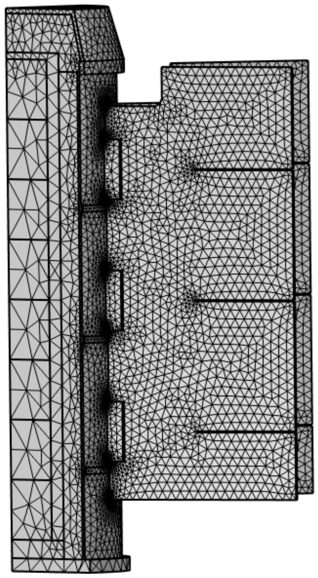

Figure 7: Meshed MMRTG quarter slice

Explanation: To reduce computational strain the MMRTG, which has axial symmetry, was cut into quarters. This quarter slice of the assembly was imported into COMSOL and meshed in preparation for analysis.

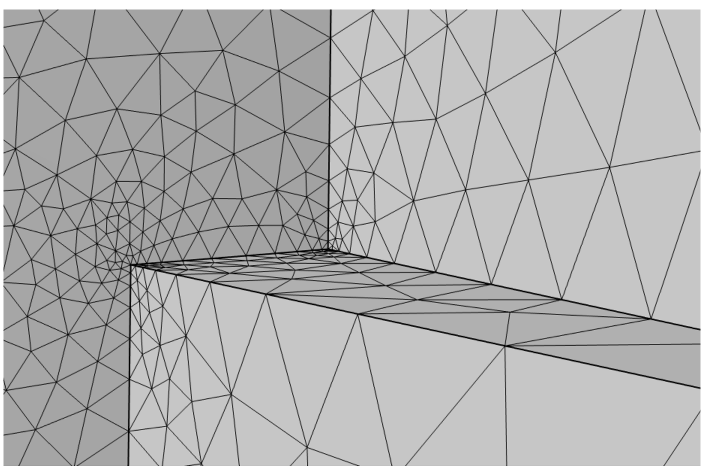

Figure 8: Wing to Shell Connection Mesh
Explanation: Finer mesh elements were used on more detailed portions of the MRMTG. The connection between the wings and shell of the MMRTG required extremely fine mesh elements in order to accurately measure the stress at that location during testing.

VI. Conclusion

The structural analysis of the MMRTG revealed that the wings and their connections to the shell are the most vulnerable components, experiencing the highest concentrations and significant displacement underload. Stress was primarily localized at the wing-shell connectors, while displacement was most pronounced at the top and bottom edges of the wings, indicating a flexural response to applied forces. These findings suggest that the current wing design may compromise the system's stability and longevity, particularly in high-gravity or high-impact scenarios. To enhance the MMRTG’s durability, future work will focus on optimizing the wing-shell connection through improved modeling, material reinforcement, or alternative design strategies. Strengthening these critical areas will improve the system’s resilience, ensuring reliable performance in demanding environments. Additionally, refining simulation techniques, such as employing finer meshing and advanced material modeling, will provide more accurate stress and displacement predictions. These efforts aim to bolster the MMRTG’s structural integrity, supporting its role in long-term space missions while maintaining safety and operational efficiency.

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