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FEASIBILITY STUDY AND SYSTEM ARCHITECTURE OF RADIOISOTOPE THERMOELECTRIC GENERATION POWER SYSTEMS FOR USMC FORWARD OPERATING BASES

by

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June 2013

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FEASIBILITY STUDY AND SYSTEM ARCHITECTURE OF RADIOISOTOPE THERMOELECTRIC GENERATION POWER SYSTEMS FOR USMC FORWARD OPERATING BASES

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ABSTRACT

This study sought to identify the feasibility of utilizing a radioisotope thermal (thermoelectric/stirling) generator to provide power to a deployed USMC Expeditionary Force. The conceptual system architecture was constructed through use of the systems engineering process, identifying necessary subsystems and integration boundaries. Radioisotope comparison was then performed, utilizing weighted design factors. It was determined that Sr-90, Cs-137, and Cm-244 would be the most effective fuel sources for this mission area. By analyzing current thermoelectric technology, it was determined that maximum system efficiency is limited to 10–15 percent when utilizing available lead telluride thermoelectrics. Barriers to development of identified physical subsystem components were then identified, including health and environmental hazards of potential isotopes, as well as shielding criteria. The system development was found to be feasible and additional design work and development work is proposed.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALSEP	Apollo Lunar Surface Experiments Package
Am	Americium
CBRN	Chemical, Biological, Radiological, or Nuclear
Cm	Curium
Cs	Cesium
DoD	Department of Defense
DOE	Department of Energy
E^2O	Expeditionary Energy Office
ExFOB	Expeditionary Forward Operating Base
GPHS	General Purpose Heat Source
GREENS	Ground Renewable Expeditionary Energy Network System
HSI	Human System Integration
IED	Improvised Explosive Device
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NASA	National Aeronautics and Space Administration
NPS	Naval Postgraduate School
ONR	Office of Naval Research
Pm	Promethium
Po	Polonium
Pu	Plutonium
RTG	Radioisotope Thermoelectric Generator
Ru	Ruthenium
S&T	Science and Technology
SE	Systems Engineering
Sr	Strontium
TPV	Thermo photovoltaic
USMC	United States Marine Corps

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EXECUTIVE SUMMARY

The battlefield energy requirements of U.S. military deployed units is trending upward, and will continue to do so in the future. Current military research groups, including the USMC Expeditionary Energy Office seek to offset this rise in demand by incorporating a combination of energy efficient equipment and practices, and new production technologies, to reduce the theater demand for fossil fuels. To that end, research into alternative energy must be performed in the present, so that the Marine Corps of the future will not be restricted with regard to mission capability.

This study analyzed the feasibility of one specific type of energy production equipment, the radioisotope thermal (thermoelectric/stirling) generator. This analysis was performed using the systems engineering method, starting with problem definition and background analysis. Initial functional and physical system architectures were developed, in order to identify needed subsystems, and to establish a baseline for future integration requirements.

Subsystem analysis was performed by identifying functional and physical possibilities and then ranking them based upon numerous identified criteria and carefully determined weighting factors. This preliminary analysis was used to determine that the most suitable radioisotopes for the USMC deployment mission were Strontium-90, Cesium-137, and Curium-244. Similar analysis within the thermoelectric subsystem identified nanotechnology produced lead telluride thermoelectrics as some of the most suitable thermoelectric energy conversion devices currently available. Integration of these subsystems yields an initial estimation of 10–15 percent system efficiency.

A preliminary catalog of barriers to production was created, along with a risk mitigation plan to follow during project design and development. It was found that the risk management plan for DoD acquisitions should be used throughout the development process to maximize system effectiveness.

Future work that was identified includes further research into each identified subsystem, as well as the determination of an operational concept from functional and

physical architecture choices. Additional barriers to implementation for each physical component should be researched, in order to identify additional needed subsystems and requirements. Incorporating additional potential stakeholders into the design process, such as the Office of Naval Research must also be performed, in order to make efficient use of joint technology, and to identify other potential mission areas. Finally, the cost and performance models should continue to be revised with stakeholder and technical expert input to improve the fidelity and usefulness of the model.

Though further research is needed, the work performed thus far indicates that providing battlefield energy in this manner is possible, and it will help to reduce the fossil fuel burden currently faced by deployed forces.

I. INTRODUCTION

A. BACKGROUND

In recent years, operational energy consumption has grown exponentially. The reasons for this are simple, yet necessary, and stem from advances in technology and the improved ability to arm and protect front line soldiers. The units of today carry more electronics, both personal and professional, into the field. They drive faster, more heavily armed and armored vehicles, and more of them. They increasingly use technology to perform jobs that were previously done through manual labor. These things have led to a battlefield energy requirement that is five times greater than it was in the 1980s (Marine Corps Expeditionary Energy Office, 2011, p. 8).

The majority of battlefield power is generated from the consumption of fossil fuels. The Marine Corps uses more than 200,000 gallons of fuel per day in Afghanistan (Marine Corps Expeditionary Energy Office, 2011, p. 7). Though the fuel is available and technology utilizing it is established, providing power in this manner is not without drawbacks. By relying on a power source that is not self-sustaining, such as diesel fuel, Marine units are tethered to a logistical supply line, requiring near constant resupply due to transportation and storage limitations. The logistical tether restricts operational movements to a radius that can be supplied, or necessitates the formation of additional supply lines in order to achieve further reach into an operational area. This resupply is normally accomplished by the use of fuel convoys, generally trucks loaded with diesel fuel that travel to an operating base, unload, and travel back to a logistical hub. Along with fuel, these convoys bring a host of potential problems. They tend to alert the enemy to base locations and troop movements, potentially placing lives and equipment at risk. The convoys themselves are in jeopardy. A recent study showed that one in every 17 fuel convoys in Afghanistan was targeted by an improvised explosive device (IED), leading to the death of one Marine per every 50 fuel convoys (Marine Corps Expeditionary Energy Office, 2011, p. 7). Reducing the frequency or size of the convoys would remove some of this risk of attack, potentially saving lives and achieving greater operational freedom.

The purpose of this thesis is to perform an initial analysis and feasibility study into a possible method of providing autonomy to expeditionary units, thereby reducing their dependence on fuel convoys. By utilizing a long-term radioisotope power system, it may be possible to reduce the unit's dependence upon these fuels. The specific power system to be analyzed is the radioisotope thermoelectric generator (RTG)

Radioisotope thermoelectric generators are devices that utilize the decay particles of radioactive elements to generate electricity. An RTG makes use of an isotope with known characteristics that emits particles as it decays. The heat from these particles is converted to electricity through the use of thermocouples. RTGs make use of radioisotopes with long, known half-lives, which allows them to function for long periods of time without adding additional fuel. It is possible that RTGs can be utilized in a previously unused manner to effectively provide power to deployed units. If so, the unit operational effectiveness could be positively affected, leading to a more efficient fighting force. This report will seek to perform a preliminary investigation into this technology to determine its feasibility.

B. METHODOLOGY

This thesis uses systems engineering (SE) methodology to attempt to determine the ideal solution for the identified problem. The proposed and selected SE process model for this work is the 2003 model for DoD Systems Engineering, shown in Figure 1.

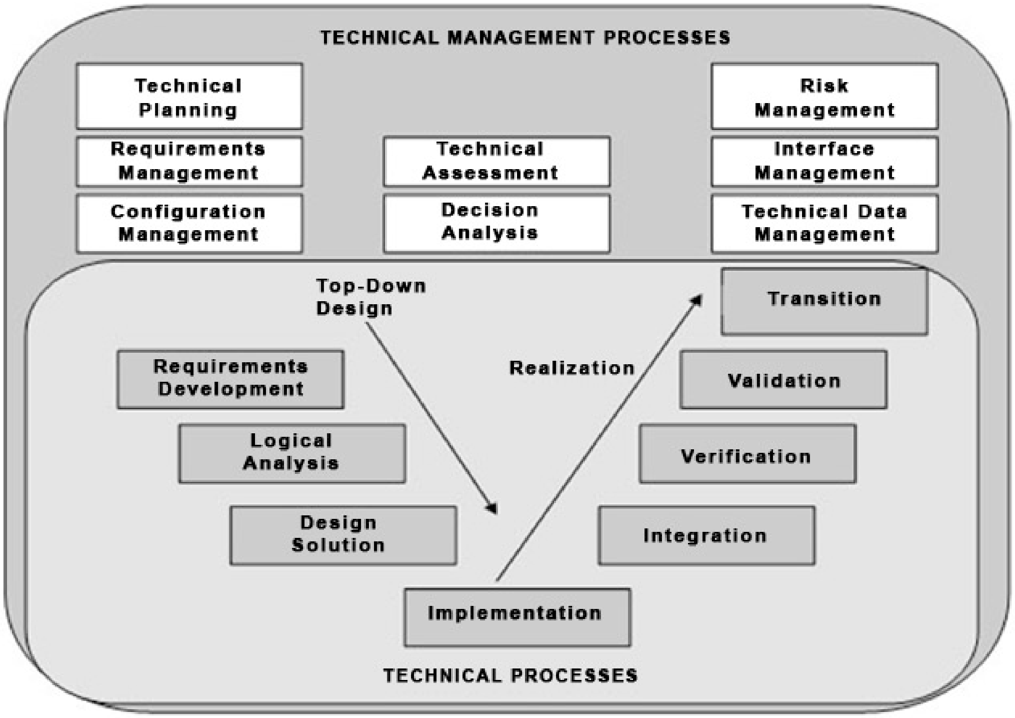

Figure 1. 2003 DoD systems engineering process model (From Defense Acquisition University, 2012)

This top-down, output driven model is utilized to ensure that the final product, if found to be feasible, is the best solution to solve the stated problem. Though the model does not illustrate it specifically, it must be understood that each process performed will be iterative, with successive work driving needed changes to previously performed work, and with the realization processes being specifically analyzed to ensure they fully manage the design processes. This thesis focuses on the design processes shown above, with a final goal of determining a preliminary systems architecture.

The first step is to fully understand the problem, in order to write a complete, yet attainable, problem statement. This problem statement is the basis for all future work performed in the project. Utilizing insight gained from creating the problem statement, all relevant stakeholders are identified and analyzed. Performing this work ensures that the problem statement is correct, and allows a needs analysis to be performed. The needs analysis seeks to identify the needs that each stakeholder has relating to the project, while also determining their interest level with regard to the project development phase. This step is necessary to ensure that proper feedback is being sought from relevant stakeholders throughout the design process. From the problem statement, system requirements are developed, which are utilized in all further design steps to ensure that the system is able to serve its proposed use. Performing this step after identifying and describing stakeholders allows all interested stakeholders the opportunity to provide input into the system requirements, ensuring that the finished product will meet their needs. Though it will be subject to continuous iteration, completion of this step completes the Requirements Development block in the proposed process model.

The next set of steps performed is identified in the SE process model as Logical Analysis. Following requirements writing a functional decomposition is developed, with each function carefully described, so that the problem can be broken down into its component parts, allowing further insight. From the functional decomposition, a physical decomposition is constructed, the function of which is to identify elements that can be used to accomplish the previously defined functions. The physical decomposition identifies any physical objects that may be able to perform the needed functions. The next analysis steps determine the options that best perform needed functions, ensuring that the stakeholder needs are met in the most effective manner possible. This requires the development of a number of decision matrices, the object of which is to rank physical components with regard to their effectiveness. To do this, criteria are established on which the objects will be scored. Weighting factors are then applied to each set of criteria, giving an overall value for each physical element. It is imperative that the decision matrix criteria and weighting factors are applied properly, or a less desirable object could be selected.

System preliminary architecture must be developed to ensure design system fidelity. This architecture identifies any objects involved with the RTG system, as well as processes that must be performed for it to be functional. Mapping these objects and processes together creates a preliminary architecture that defines subsystem interrelationships and ensures interoperability. It also serves to show additional objects or processes that should be included in the design.

C. PROBLEM STATEMENT

On August 13, 2009, the top levels of the United States Marine Corps declared energy a top priority. This led to the formation of the USMC Expeditionary Energy Office (E^2O), whose job would be to help develop that priority into a physical need, and further turn it into reality. The E^2O promptly developed a demanding mission statement:

> By 2025 we will deploy Marine Expeditionary Forces that can maneuver from the sea and sustain its C4I and life support systems in place; the only liquid fuel needed will be for mobility systems which will be more energy efficient than systems are today. (Marine Corps Expeditionary Energy Office, 2011, p. 17)

Simply put, the Marine Corps is seeking to reduce its dependence on fossil fuels, to the point of eventually fueling expeditionary forces without relying upon fossil fuels except for transportation. To accomplish this goal will require much study on multiple different energy fronts, with a determination made as to the most effective ways to provide power.

The problem investigated by this study is to determine whether RTG systems can be used to help accomplish the E^2O mission statement. Specifically, whether RTGs can be a feasible part of an expeditionary unit energy plan with regard to power generation capability, weight, physical dimensions, cost, or other performance characteristics. This report seeks to perform many functions. For the study to be useful, the potential benefits of the technology to the Marine Corps must be established. To this end, the state of current RTG technology is investigated, including instances in which these generators are functioning, or have functioned in the past. The author seeks to characterize potential USMC missions and equipment that could make use of the technology, and utilizes systems engineering methodology to determine the proper radioisotopes and power generation equipment that will best accomplish these missions. From this data, a concept of operations is described, seeking to determine the RTG's potential purpose within the expeditionary group, as well as its overall effects on the unit. The initial RTG system architecture is developed in order to determine necessary system and user interactions. Recommendations are then made with respect to the technology, including if it should be incorporated, in what manner, and in what types of equipment. Finally, it is necessary to define future work that must be done to continue the project to the overall end goal of fielding an operational unit.

D. STAKEHOLDERS

1. USMC Expeditionary Energy Office (E^2O)

A primary stakeholder for this report is the USMC Expeditionary Energy Office (E^2O), a department formed in 2009 in order to focus and direct the United States Marine Corps' energy strategy for the future. E^2O focus is on driving toward completion of the following mission statement:

> By 2025 we will deploy Marine Expeditionary Forces that can maneuver from the sea and sustain its C4I and life support systems in place; the only liquid fuel needed will be for mobility systems which will be more energy efficient than systems are today.

The E^2O focuses on the following areas of study to drive their mission statement.

1. Guiding Power and Energy S&T Enabling Capabilities
2. Establishing new Training and Doctrine
3. Including energy performance into Requirements and Acquisitions decisions
4. Mitigating investment risk and building confidence in new equipment capabilities through the Experimental Forward Operating Base (ExFOB) process.

The needs of the E^2O are both complex and long-term. The basic need of the office is to develop ways to maintain U.S. Marine Corps relevancy and necessity in both the near and far term. To this end, the office has been entrusted with developing ways to use energy more efficiently, in order to reduce the service's demand for fossil fuels.

E^2O interest should remain relatively high throughout the process, from investigation to development and verification, but interest will increase further as testing is performed to determine real-world data and integration techniques. The reason for this is the E^2O is interested in actual methods of fossil fuel reduction. The office values all studies assisting in the goal, and will take an active role in its final execution.

This study is of potential interest to the E^2O because of its support for focus 1. The report is intended to be a preliminary investigation into the new use of a way to deliver power to units. It is likely that the use of RTG technology could be integrated into the power system of the future, aiding deployed units in their efforts to increase capability. E^2O is interested in any technologies that could aid in the development of a total energy system, an efficient and effective means of providing power to the equipment and Marines of the future.

The final product should also support focus 2, since inception of new technology should include human systems integration (HSI) factors, technical and specifications manuals, and operational instructions. The study will also include a determination of necessity for operator schooling or education, or job training specifics.

2. Naval Postgraduate School

Another primary stakeholder is the Naval Postgraduate School, specifically the student researchers and instructors involved in this thesis, as well as other energy-related studies. Accomplishing an eventual goal of a total, efficient, integrated power system will only be the result of years of academic study, construction and testing, and eventual verification. To this end, any reports on efficient or alternative energy sources, as well as those focusing on the efficiency of power generation and distribution systems are relevant areas of study within the scope of the project.

The needs of academia at this point are complex and varying. Preliminary studies into RTG technology requires research involving data points, many of which have been measured previously. By developing needs and requirements, academic students can create preliminary, feasibly operational concepts by understanding and applying past uses of the technology, understanding new needs and requirements, and marrying functional requirements to physical processes. Researchers at this point have informational needs related to requirements development, primarily relating to the characterization of USMC operations and equipment. Following the development of an operational concept, needs of academia will involve funding for technology development and testing. It is expected that academic interest in the project will remain high throughout the development and testing phases of the project.

3. USMC Expeditionary Units

Though the E^2O is only one small part of USMC Operations, the office has the potential to greatly affect the overall operations of the USMC, so it is necessary to understand and eventually classify Marine Corps Operations, within the scope of energy usage.

While one of the main focuses of the USMC is power projection from the sea, the force plays a vital role in ground operations all over the world. Having played a vital role in countless combat, defense, humanitarian assistance, and disaster relief operations all over the world, this relatively small force of 200,000 active and 40,000 reserve personnel plays a vital role in protective U.S. interests.

USMC interest in the project is similar to, but perhaps less focused than E^2O interest. While E^2O is interested in on energy production and usage on a global scale, individual USMC units are interested in the effects on the individual Marine. It is difficult for a unit, especially an individual Marine, to understand the implications of his power usage. While training and education can attempt to close this knowledge gap, the primary goals of the unit will be upon increasing operational effectiveness, reducing unit capability gaps, and easing the burden of a deployed lifestyle.

Needs for expeditionary units are related to the physical composition and performance characteristics of the power generation equipment. With a primary mission of power projection from the sea, expeditionary units must be adequately mobile through the sea, air, and land domains. Size and weight of equipment is therefore of extreme importance. Current alternative energy technologies, such as the Ground Renewable Expeditionary Energy Network System (GREENS), weigh over 300 pounds and take up over 16 cubic feet of space to provide 300 Watts of electrical power. Technology that can reduce this weight or volume, or increase the amount of power provided will ease the transportation burden on the units, making them more agile and operationally efficient.

Expeditionary unit interest in RTG development will initially be low, as the unit is operationally focused. Interest will rise during the testing phase and be highest during and after the field testing of final generator designs.

4. Department of Energy

DOE has few specific needs relating to the preliminary investigation of the project. Though much of the background research used in the feasibility study comes from previous DoE investigations, this data is publicly available and will be used primarily to determine the functionality of various sources, power producing equipment, and proposed future technology.

DoE interest in the project is very low initially. Interest will rise as a true operational concept is proposed, as the concept may involve production of radioisotopes not currently available. Interest will remain high throughout the design lifetime, as the DoE provides oversight for all U.S. nuclear programs and technology.

5. U.S. Navy

The United States Navy is the largest naval force in the world, in terms of sheer tonnage. It is comprised of a large and varied mix of ships, aircraft, and personnel, and is able to project power on a global scale in a continuous manner, unlike any other service. The goal of the navy is summed up in its mission statement: The mission of the Navy is to maintain, train and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas (U.S. Navy, 2006).

To this end, the service must be constantly seeking ways to maintain its operational capabilities. One of the major military innovations in recent years has been the proliferation of unmanned and autonomous systems, such as the MQ-9 Reaper and MQ-1 Predator drone aircraft. These systems have proven their worth in combat and reconnaissance missions, allowing intelligence gathering and power projection without placing allied human lives at risk. The Navy is developing future unmanned and autonomous systems through a number of groups, such as the Office of Naval Research (ONR). The vision of the ONR sums up the Navy's understanding of this critical technology:

> Achieve an integrated hybrid Force of manned and unmanned systems with the ability to sense, comprehend, predict, communicate, plan, make decisions and take appropriate actions to achieve its goals. The employment of these systems will reduce risk for Sailors and Marines and increase capability.

In the sea domain, it is likely that these unmanned systems would need to operate for extended periods of time without physical human interaction. For this to occur, the systems would need a long-term, stable, independent power supply. A fully developed RTG could fit this need perfectly, allowing long range, long term, autonomous operations to occur.

The needs of the Navy are not established at this time, but will involve the development of a safe, effective power supply with acceptable performance qualities. These qualities would be based upon the platform utilizing the RTG, but overall needs would be for the power supply to be light, of sufficient power, self-operable, and long-term.

U.S. Navy interest will be low initially, and rise as RTG specifications are determined. At this point, it is likely that researchers will attempt to determine any potential platforms on which the technology would be useful. If deemed feasible, Navy interest will continue to rise throughout development.

6. Department of the Air Force

In a manner similar to the Navy, Air Force workers are interested in the future use of unmanned and autonomous systems. It is conceivable that the RTG technology could be utilized to provide power to an aerial vehicle, which would provide the ability to continuous, long-term flight and constant surveillance.

The needs of the Air Force are not established at this time, but will be heavily involved in production of a light, sufficiently energy dense power supply.

USAF interest in the project will be low initially, but may rise as RTG specifications are determined. At this point, it is likely that researchers will attempt to determine any potential platforms on which the technology would be useful. If deemed feasible, USAF interest will continue to rise throughout development.

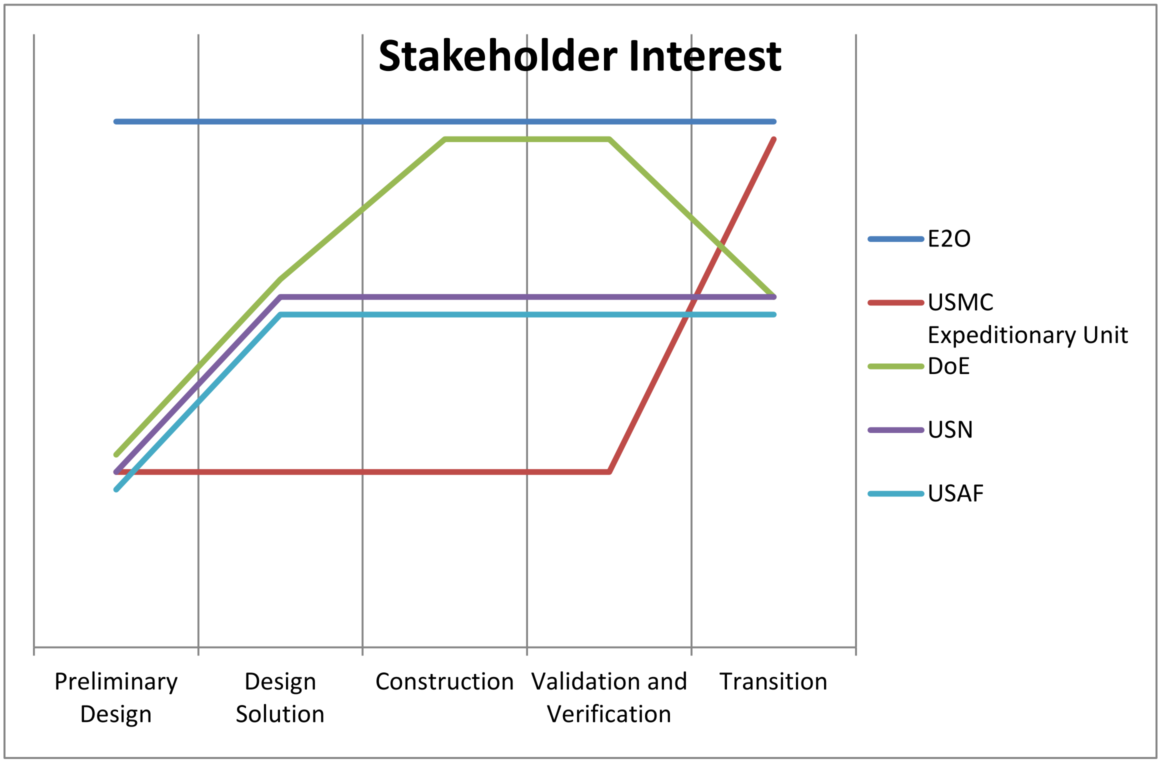

Figure 2. Stakeholder interest throughout development process

E. CURRENT RTG TECHNOLOGY

The use of RTGs as a source of electricity is not a new idea. Mound Laboratories, as a research center for the Atomic Energy Commission (later the Department of Energy) created the United States' first RTGs in the 1950s. RTGs have served many functions in the past decades, but their ability to provide power for extended periods of time with no human interference has made them especially well-suited for some very specific operations.

Amongst American companies, National Aeronautics and Space Administration (NASA) has made use of RTG technology, perhaps more than any other.

1. List of NASA Uses

The SNAP-19B was NASA's first attempted use of RTG technology, and was set to launch in 1968. The device was the planned power source for the Nimbus III satellite, providing 28.2 Watts of thermal power. Though the launch vehicle failed at takeoff, the RTGs were recovered for future use.

The SNAP-19 RTG was used successfully by NASA as the power supply to the Viking Mars landers in 1975. The 40.3 Watt RTGs successfully powered the 2 landers for 6 and 4 years, though their operational design requirement was just 90 days.

The SNAP-19 RTG was further used to power the Pioneer 10 and 11 spacecraft, which were launched in 1972 and 1973, respectively. These 42.6 Watt RTGs were still operating 30 and 22 years later, when communications with the spacecraft were lost due to their distance traveled.

The SNAP-27 RTG was used by Apollo missions 12, 14, 15, 16, and 17 to provide power to the Apollo Lunar Surface Experiments Package (ALSEP). ALSEP was a series of stations left on the moon used to transmit information about moonquakes, meteor impacts, magnetic and gravitational fields, and the Moon's internal temperature and atmosphere. The stations operated for years with all power provided by the SNAP-27. The 3.8 kg initial Pu-238 fuel load provided a total of 70 Watts of initial power, while still providing >90 percent power after 10 years operation (National Air and Space Museum, 1999).

The Multi-Hundred Watt RTG was a 158 Watt generator, which was used to power the Voyager 1 and 2 spacecraft, which were launched in 1977. They are currently still operating at the edge of the solar system.

General Purpose Heat Source (GPHS) RTGs were used as the power source for the Galileo, Cassini, Ulysses, and New Horizons spacecraft. The Cassini and New Horizons craft are still operating, while the Galileo operated for 14 years, and the Ulysses for 19 years.

The current generation of NASA RTG is the Multi-Mission RTG (MMRTG), which was developed to provide a minimum lifetime of 14 years, while minimizing weight and providing adequate safety. The MMRTG was launched in 2012 and is currently being used to power the Mars Rover. The MMRTG contains 4.8 kg of plutonium dioxide, which creates an initial 2000W of thermal power and 120W of electrical power. The MMRTG generator is 64 cm in diameter, 66 cm long, and weighs 45 kg.

2. Military Uses

The United States military has made numerous uses of RTG technology. Possibly the most famous example was the U.S. Navy's 25W generator, which was installed in 1966 at Fairway Rock, Alaska. This generator was used to power oceanographic sensors. It was removed in 1995, at which time the RTG was still operating.

Similar RTGs have been used, mostly in the Arctic and Antarctic regions, to power sensor data and long-term weather equipment. Specific applications can be found in the report, Radioisotope Thermoelectric Generators of the U.S. Navy, Volume 10. Though nearly all of these RTGs have functioned well, almost all military applications of RTGs have been removed from service, and none are currently in development.

There are a number of past Soviet applications of RTG technology, though no new applications have been created in the past few decades. Their extensive use of RTGs was mainly limited to between 10 and 200W power supplies for unmanned lighthouses and beacons. Though some of these generators are still functioning, many have fallen into disarray, or have had crucial parts scavenged by thieves. (Rumyantsev, 2003, p. 2). The fate of these old, outdated RTGs is currently not resolved, though their years of successful service without human interaction illustrate the possible usefulness of the technology.

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II. CONCEPTUAL DESIGN

A. FUNCTIONAL DECOMPOSITION

To begin the proposed system analysis, it is necessary to identify all necessary functions in the development of a traceable functional architecture (or functional decomposition). This process was used to assist in the identification of needed subsystems and ensure that stakeholder needs can be traced all the way to evaluation metrics, as well as providing a means for functional allocation to possible physical solution components. After physical elements are selected for each identified subsystem, they can be traced back to the functional decomposition, to ensure that the system will function as intended. The initial decomposition is shown in Figure 3. Top level functions were identified by analyzing previously used RTGs to determine similar characteristics and contrasting that with the proposed usage by an expeditionary force, which would possess additional characteristics such as mobility and non-autonomy.

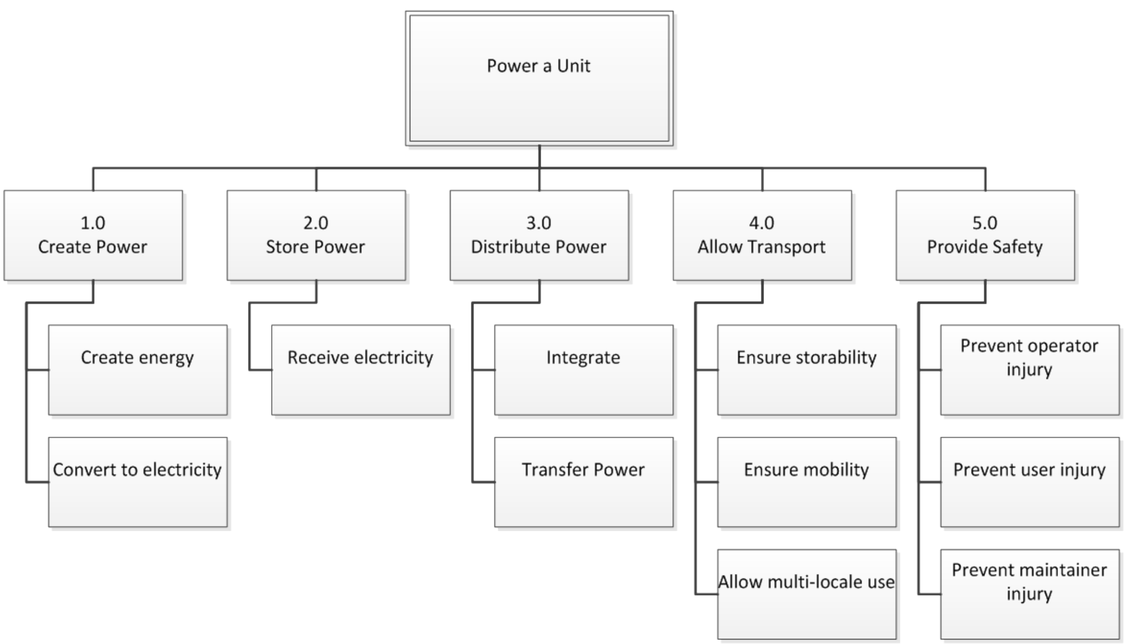

Figure 3. Functional decomposition

1. Function 1.0 Create Power

This function is defined as the generation of electrical power in a usable quantity. It includes the subfunctions of the creation of energy, and the conversion of that energy into electricity. The energy creation should occur without regular fuel input from an operator.

2. Function 2.0 Store Power

This function is defined as the storage of a finite amount of energy until such time as it is needed by a load. It includes the subfunction of receive electricity. This energy storage should occur in such a manner as to allow the receipt of the specified amount of power to the load at all times.

3. Function 3.0 Distribute Power

This function is defined as the providing of power to the load in sufficient quantity. It includes the subfunctions of integrate, as the power production and storage elements must coexist with the distribution node and load, and transfer power, which sends electricity to the load.

4. Function 4.0 Allow Transport

This function is defined as ensuring portability of the system, meaning that it can operate in multiple locations with relative operator ease. It includes the subfunctions of ensure storability and ensure mobility, in order to allow the system's use in a deployed location.

5. Function 5.0 Provide Safety

This function is defined as prevention of the system from causing harm to operators, users, or the environment in any measurable way. It includes the subfunctions of preventing injury to users, operators, and maintainers.

B. PHYSICAL DECOMPOSITION

The physical decomposition (Figure 4) is necessary to begin the process of identifying physical possibilities to perform the functions that must occur. This decomposition also serves as the initial physical architecture, and will be used to develop an integration plan for needed subsystems. The ultimate system architecture (combining both functional and physical architectures) envisioned is that of a system of systems, integrated to yield efficient power production, storage, and distribution capabilities. This system of systems may take advantage of any number of available technologies, either conventional or alternative energy. Though this thesis decomposes the radioisotope fuel and thermoelectric elements subsystems, other subsystem physical components must be identified prior to analysis.

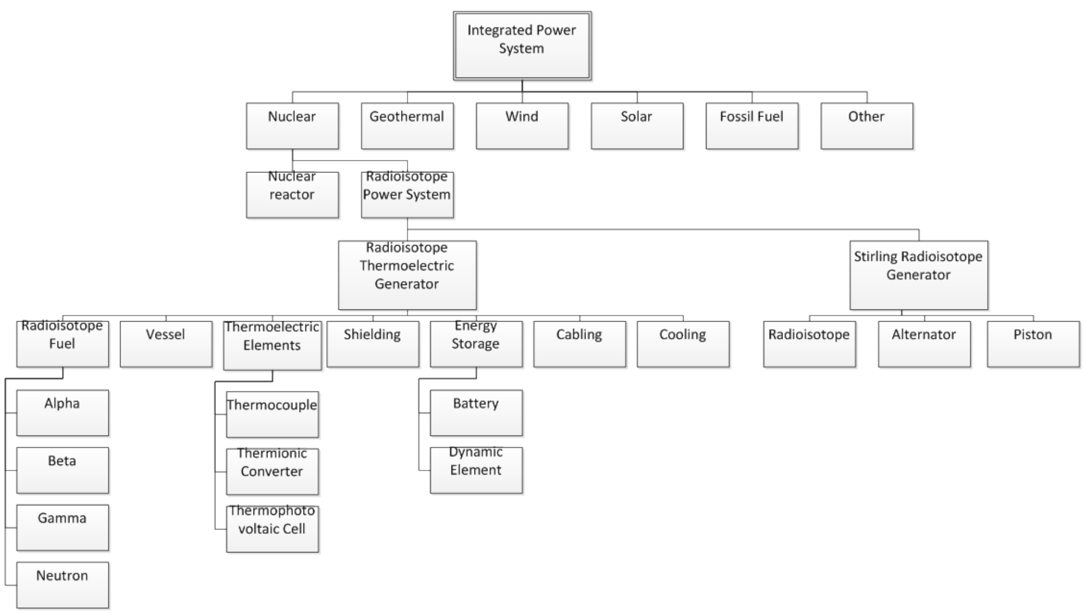

Figure 4. Physical decomposition

1. Subsystem Definitions

Fuel: The radioisotope compound used as an energy source

Shielding: The parts of the RTG utilized specifically to attenuate radiation

Thermoelectric elements: The elements of the RTG that convert heat from the radioisotope into usable electrical energy

Energy Storage: The elements of the RTG used to store energy that is not immediately used

Cabling: The elements of the RTG used to transfer power or information across subsystems

Cooling: The elements of the RTG used to maintain the temperature of the cool side of thermoelectric elements

Vessel: The elements of the RTG utilized for structural support and protection from outside forces, such as enemy actions

Stirling Engine: A dynamic engine that utilizes a heat difference to drive an element in a cyclic motion

For the purposes of this thesis, in-depth analysis is performed on the radioisotope fuel and thermoelectric elements subsystems, in order to determine their feasibility.

C. REQUIREMENTS

Requirements should be generated with the drivers of size and weight as a premium. The following regulations illustrate the lifting capacity of USMC equipment, and were used as background information.

1. Lifted by Marines / Loose Cargo: One person lift – 44 pounds
2. Requiring Forklift / Material Handling: > 400 pounds
3. HMMWV Trailer Towable: > 2700 pounds
4. Medium Tactical Truck Carried: < 7 tons (off road), 10 tons (on road)
5. Heavy Tactical Truck Carried: < 16 tons (on road)
6. MV-22 Tilt-Rotor Lift: < 4 tons (internal), 7.5 tons (external)
7. CH-53 Helicopter Lift: < 5 tons (internal), 14 tons (external) (Govar, 2011, p. 5)

For the purpose of this thesis, analysis was performed using the assumed requirement of production of 300 watts of electrical energy under all conditions. This value was chosen to allow direct comparison of the RTG system to GREENS and other alternative energy technologies available. Performing the analysis in this manner allows a preliminary performance and cost comparison to be made.

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III. OVERVIEW OF RADIOISOTOPES

A. RADIOISOTOPE BACKGROUND

In order to determine the proper ranking for possible radioisotopes, it is necessary to understand the types of particles they emit, and how these particles interact with surrounding materials. There are four main types of radiation particles: alpha, beta, gamma, and neutron.

Alpha particles are identical to a Helium nucleus, with the particle being made up of two protons and two neutrons. For this reason, they are frequently referred to as He-4, ${}_{2}^{4}He$, or ${}_{2}^{4}\alpha$. Isotopes that decay by alpha emission tend to be very large (atomic number greater than 81), and have a high ratio of neutrons to protons. (Environmental Protection Agency, 2012a) The emission equation is as follows:

$${}_{Z}^{A}X \rightarrow {}_{z-2}^{A-4}Y + {}_{2}^{4}\alpha$$

Alpha particles are relatively heavy and slow moving, with a speed about one-twentieth as fast as a gamma particle. They are also highly charged, carrying no electrons and a +2 charge. For these reasons they interact heavily with most matter, including air, and do not travel far. They are unable to penetrate most matter, and are unable to pass through the dead outer layers of human skin (Environmental Protection Agency, 2012a). For these reasons, external exposure to alpha radiation is typically of little consequence. Of much greater concern is ingestion or inhalation of alpha sources, as they are highly toxic. Once inside the body, the alpha particles can affect living tissue, and increase the risk of adverse effects such as cancer. In particular, alpha particles are known to cause lung cancer when inhaled. For these reasons, solid chunks of alpha emitting radioisotopes are easily shielded and not a major health risk, but powders or small edible pieces can be a cause for much concern.

Beta particles are identical to electrons and, as such, carry a charge of -1. They are frequently shown in equations as e, β^{-}, or ${}_{-1}^{0}e$. Beta particles are emitted in isotopes where to ratio of neutrons to protons is too high. During beta emission, a neutron is converted to a proton and a beta particle. The proton remains in the nucleus and the beta is ejected with a finite amount of energy. The ejection is sometimes accompanied by the release of a gamma particle. A basic beta decay equation is shown below.

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e $$

Betas are lighter, faster, and more lightly charged than alphas, causing them to travel much further distances in air. They interact strongly with matter, however, and are relatively easily shielded. External exposure to beta particles is not a health concern, as they are unable to penetrate the dead outer layers of skin. Similar to alpha particles, the major exposure risk from beta emitters comes from cases in which they are inhaled or ingested.

Beta particles do, however, cause a secondary effect that can be problematic. Bremsstrahlung is caused by the slowing down of a charged particle due to its interaction with another charged particle. In the process of slowing, beta particles, whose speed is dependent upon their energy, may emit energy in the form of a gamma ray. These gamma rays are highly penetrating, and can pose an external radiation exposure risk.

Gamma rays are particles that have no mass or charge. They travel at the speed of light and interact lightly with most types of matter. For these reasons they are highly penetrating, causing gamma emitters to offer both an external and internal exposure risk. Due to the small interaction, gamma particles are less effective at creating thermal energy than alphas and betas, and require more shielding to prevent nearby personnel from obtaining a significant amount of radiation exposure. Gammas are emitted from isotopes that have an energetic nucleus, but the proper ratio of protons and neutrons. They also frequently accompany beta emission.

Neutron emission is often a component of fission or spontaneous fission. Neutrons have mass but no charge and, as such are less penetrating than gamma rays, but much more penetrating than alpha and beta particles. Over time, they can cause surrounding equipment to become irradiated or brittle and are of little use as a source of energy. Exposure to a neutron flux will result in an external dose, so a source must be shielded effectively to be safe.

The biological effects of different types of radiation are shown by the use of the Radiation Weighting Factor (RWP), which compare damage caused by different types of particles. The factors for particles of interest are shown in Table 1.

Table 1. Particle weighting factors (After ICRP, 1991, p. 3)

Type	Radiation Weighting Factors
Gamma	1
Electron (Beta)	1
Neutron (energy dependent)	5–20
Alpha	20

From Table 1, it can be seen that tissue interaction with an alpha particle can be approximately 20 times more damaging than interaction with a beta particle.

B. RADIOISOTOPE DATA

Isotopes suitable to be used as fuel in an RTG are determined by a number of criteria. The isotope must produce high energy radiation to be effective as a power source. The half-life must be long enough that the isotope releases suitable energy at a relatively constant rate for a significant amount of time. The fuel must produce a suitable amount of power per volume. These criteria have historically limited the number of choices to just a few isotopes, which have all been used in various ways. Previous, widely used isotopes as RTG fuel sources are Plutonium-238, Strontium-90, Polonium-210, and Americium-241. These are not the only isotopes that create usable radiation, so additional research is warranted.

Apart from the amount of thermal energy produced, a major factor in determining suitability of a radioisotope is simply the type of radiation emitted, stemming from the type of decay of the element. There are 4 major types of decay which must be understood in order to use them as selection criteria: neutron, alpha, gamma, and beta.

1. Plutonium-238

Pu-238 is an isotope of Plutonium that decays almost exclusively as a result of emitting alpha particles, into U-234. It has a long half-life of 87.7 years, and a relatively high thermal energy output of 0.54 W per gram of material. Pu-238 does not occur naturally and therefore must be created. The mechanisms under which Pu-238 can be produced are by the neutron irradiation of either Neptunium-237 or Americium-241. The production and decay equations are as follows:

$$\text{Np-237 + n} \rightarrow \text{Np-238}\left(\beta\text{ decay in 2.1days}\right) \rightarrow \text{Pu-238}$$

$$\text{Pu-238} \rightarrow \text{U-234} + \text{He-4} + \text{5.6MeV(average)}$$

Pu-238 has traditionally been used in space exploration applications, but is very infrequently used in terrestrial applications. This is presumably due to its relatively long half-life and high thermal output, making it ideal for long-term projects where reducing equipment size and weight is more important than minimizing fuel production costs.

Pu-238 is not fissionable and therefore of no use in nuclear bombs or other weapons. It does, however pose some hazards to personnel. As an alpha particle emitter, Pu-238 poses no external health risks. The internal risks are significant, as Pu-238 that has been inhaled or ingested tends to remain in the body for decades, increasing the risk of cancer. As a toxic metal, the isotope can also cause damage to the kidneys. (Environmental Protection Agency, 2012d)

2. Strontium-90

Strontium-90 is a byproduct of nuclear fission of Uranium and Plutonium. Strontium is produced in large quantities in nuclear power plants using these elements as fuel, and is also produced as a byproduct of nuclear weapons testing. Strontium-90 is a beta emitter that decays to Yttrium-90 at a half-life of 28.8 years. Yttrium-90 undergoes similar beta-minus decay to Zirconium-90 at a half-life of 64 hours (Environmental Protection Agency, 2012e). The decay chain for Strontium-90 is shown below.

$$^{90}_{38}Sr \rightarrow {}^{90}_{39}Y + {}^{0}_{-1}e + \overline{\nu}^{-} \rightarrow {}^{90}_{40}Zr + {}^{0}_{-1}e + \overline{\nu}^{-}$$

As a beta emitter, external exposure to Sr-90 poses little health risks. Internal exposure from ingestion or inhalation will increase the chance of contracting bone cancer and leukemia, as Sr-90 tends to deposit in bone and bone marrow. (Environmental Protection Agency, 2012e) The power density of the material is dependent upon the compound of Strontium that is produced.

3. Americium-241

Americium is not a naturally occurring element. It is produced as a byproduct of Plutonium undergoing neutron capture and, as such, is produced as a waste product in many nuclear reactors. There are three major forms of Americium produced: Am-241, Am-242(metastable), and Am-243. Of the three, Am-241 is by far the most prevalent, with the other isotopes making up only a few percent of the total Am inventory at any given power plant. For this reason, only Am-241 will be considered as a legitimate fuel source.

Am-241 is produced from the (2) neutron absorption of Pu-239, which then beta decays to Am-241. Am-241 has a half-life of 430 years and decays primarily by alpha emission, with a thermal energy output of 0.114 W per gram of material. Am-241 production and decay equations are shown below:

$$\text{Production: } {}^{239}_{94}Pu + 2n \rightarrow {}^{241}_{94}Pu \rightarrow {}^{241}_{95}Am + {}^{0}_{-1}e$$

$$\text{Decay: } {}^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^{4}_{2}He + \gamma$$

As an alpha and gamma emitter, Am-241 poses both an internal and external radiation risk. If ingested or inhaled, it can remain in the body for decades, increasing the risk of cancer to surrounding organs. If an individual is subjected to direct external exposure, radiation from gamma rays can also increase the risk of various types of cancers. (Environmental Protection Agency, 2012b)

4. Polonium-210

Polonium-210 is a naturally occurring isotope that is present in the environment in very small quantities. The natural production of Po-210 comes from the decay of Pu-238, but this produces an amount too insignificant to be useful in most applications. A ton of uranium ore would contain only about 0.0001 grams of Po-210. (Dworschak, 2006) For realistic applications, Po-210 must be synthesized. This process is performed by neutron irradiation of Bismuth-209, creating Bi-210, which then decays into Po-210. (International Atomic Energy Agency, 2013) Po-210 decays almost exclusively by alpha emission with no attendant particles. It has a relatively short half-life of 138 days but an extremely high thermal output of 140 W per gram. Po-210 production and decay equations are shown below:

$$\text{Production: } {}^{209}_{83}Bi + {}^{0}_{1}n \rightarrow {}^{209}_{84}Po \rightarrow {}^{210}_{84}Po + {}^{-1}_{0}e$$

$$\text{Decay: } {}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$$

As an alpha emitter, Polonium poses no direct external health risk. However, if ingested or inhaled, it will cause serious damage or even death. Due to its short half-life and high energy radiation, a small amount of Polonium inside the body will have severe effects. It is estimated that 3 millicuries of Po-210, equivalent in size to less than a grain of salt, could be fatal to a person weighing 70 kilograms. (United States Nuclear Regulatory Commission, 2012)

5. Cesium-137

Cesium-137 is not a naturally occurring isotope, and is produced only as a product of fission from sources using uranium or plutonium as fuel. Thus, Cs-137 is only produced in useful amounts as a waste product from nuclear reactors and nuclear weapon explosions. Cs-137 that is present in the environment comes from radioactive fallout from nuclear weapons testing, or from the release of fission products into the environment, such as in the case of Chernobyl of Fukushima. Cs-137 is used in many applications, such as in gauges or time measurement devices, as well as medically to treat certain types of cancer. Cs-137 decays by beta emission with no attendant gamma rays to either a stable or metastable form of Barium-137. Ba-137(m) emits high energy gamma particles to reach its stable ground state.

Cs-137 has a half-life of 30.17 years and a thermal output of 0.08 W per gram. Its decay equations are shown below:

$$\text{Decay: } {}^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba(m) + {}^{0}_{-1}e \rightarrow {}^{137}_{56}Ba + \gamma \text{ (95 percent)}$$

$$ {}^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba + {}^{0}_{-1}e \text{ (5 percent)}$$

As an emitter of both beta and gamma particles, Cs-137 poses both and internal and external radiation hazard. Direct exposure to this radioisotope will cause an increased risk of cancer and damage to affected organs. (Environmental Protection Agency, 2012c)

6. Ruthenium-106

Ru-106 is produced from the fission of U-235. As such, it is a waste product in many reactors using U-235 as a fuel source. Though other isotopes of Ruthenium are present naturally in small quantities, this isotope must be created. Ru-106 is used in radiotherapy of eye tumors.

Ru-106 has a half-life of 373.6 days, and a thermal output of 33.1 W per gram. Its decay equations are shown below:

$$ {}^{106}_{44}Ru \rightarrow {}^{106}_{45}Rh + {}^{0}_{-1}e $$

As an emitter of beta radiation, Ru-106 presents only an internal exposure hazard.

7. Curium-242/244

Curium is a non-naturally occurring element which is synthesized by bombarding heavy elements with neutrons. Though these isotopes decay primarily through alpha particle emission, a small critical mass will cause sustained nuclear chain reaction, emitting gamma neutron and gamma particles. Curium is used as an alpha source for spectrometers, as well as a way to begin production of heavy actinides, such as Pu-238. Production and decay equations of these isotopes are shown below.

a. Cm-242

$$\text{Production: } {}^{239}_{94}Pu + 2\,{}^{1}_{0}n \rightarrow {}^{241}_{94}Pu \rightarrow {}^{241}_{95}Am$$

$${}^{241}_{95}Am + {}^{1}_{0}n \rightarrow {}^{242}_{95}Am \rightarrow {}^{242}_{96}Cm + {}^{0}_{-1}e$$

$$\text{Decay: } {}^{242}_{96}Cm \rightarrow {}^{238}_{94}Pu + {}^{4}_{2}\alpha$$

Curium-242 has a half-life of 160 days, and a thermal output of 120 Watts per gram.

b. Cm-244

$$\text{Production: } {}^{239}_{94}Pu + 4\,{}^{1}_{0}n \rightarrow {}^{243}_{94}Pu \rightarrow {}^{243}_{95}Am + {}^{0}_{-1}e$$

$${}^{243}_{95}Am + {}^{1}_{0}n \rightarrow {}^{244}_{95}Am \rightarrow {}^{244}_{96}Cm + {}^{0}_{-1}e$$

$$\text{Decay: } {}^{244}_{96}Cm \rightarrow {}^{240}_{94}Pu + {}^{4}_{2}\alpha$$

Curium-244 has a half-life of 18.1 years, and a thermal output of 2.65 Watts per gram.

As an alpha emitter, Curium poses an internal health hazard. However, due to neutrons and gamma rays associated with spontaneous fission, these particles also present an external risk.

8. Thulium-170

Thulium is a naturally occurring element, and is extracted from mined ores such as monazite or gadolinite. Though it can be mined, thulium makes up a very small percentage of ore and, as such, is somewhat rare. The element has been used primarily in a medical capacity, as an X-ray source for cancer treatments.

Thulium-170 has a half-life of 128.6 days, and a thermal output of 13.6 W per gram. Its decay equation is shown below:

$$\text{Decay: } {}^{170}_{69}Tm \rightarrow {}^{170}_{70}Yb + {}^{0}_{-1}e$$

Primarily a beta particle emitter, Th-170 presents an internal radiation health hazard.

9. Promethium-147

Though Promethium occurs naturally, it is not prevalent enough in earth to be useful. Therefore, all commercial uses of Promethium are via manmade sources. Pm-147 is produced as a fission product waste in nuclear reactors. Promethium is used as a beta radiation source, and has been used as RTG fuel in the past.

Pm-147 has a half-life of 17.7 years and a thermal output of 0.33 W per gram. Its decay equation is shown below:

$${}^{147}_{61}Pm \rightarrow {}^{147}_{62}Sm + {}^{0}_{-1}e$$

As a beta particle emitter, Pm-147 presents solely an internal health hazard.

C. INITIAL SELECTION METHODOLOGY

In order to determine the most effective potential radioisotopes, it is necessary to create a preliminary ranking system. This was performed in three separate steps. First, initial data was gathered on radioisotope compounds meeting the following criteria:

1. Suitable half-life: this was chosen to be greater than three months, which corresponds to approximately one-half of a typical deployment length. This criteria prevents is short enough to prevent potential fuel exclusion yet long enough to eliminate a large number of rapidly decaying isotopes.
2. Suitable power production: suitability was determined by comparison with the Ground Renewable Expeditionary Energy Network System's (GREENS) Integrated Solar Panel Case Assembly (ISPCA), which weighs 65.77 kg, and produces 300 Watts of usable electrical energy, or .02 Watts/gram.
3. Data available: the compounds researched have previously been utilized in radioisotope power systems, allowing raw data to be available.

Appropriate metrics were then constructed, with each compound being ranked according to a weighted scoring system, to determine the overall suitability of each specific compound. Specific power was determined to be the highest priority factor, as power production capability is a primary risk when evaluating the feasibility of the power system.

1. Initial Selection

Table 2 includes data associated with each possible isotope. Data gathered include the type of particle(s) emitted during decay, the specific power provided by the fuel in watts per gram, the density of the isotope, the specific power provided by the finished fuel pellet compound, the half-life of the isotope, the initial cost estimate of purchasing the fuel, and the availability in terms of kilograms produced per 100 megawatts of power generated in a power plant.

Table 3 applies weighting factors generated from system experts to provide a preliminary effectiveness ranking of all radioisotopes. Performing this step allows the ability to eliminate some sources as possibilities, due to the much greater effectiveness of other options. It also allows the ability to determine the effectiveness of each fuel source under various mission areas by changing the weighting factors.

Table 2. Radioisotope data

Isotope	**Particle Emitted**	**Specific Power (W/g)**	**Density (g/cm3)**	**Compound Specific Power (W/g)**	**Half-life (yr)**	**Cost ($/g)**	**Availability (kg/100MweY)**
Sr-90	Beta	0.96	2.6	0.22	27.7	20	16
Cs-137	Beta/Gamma	0.42	3.42	0.12	30	6.5	36
Po-210	Alpha	141.3	9.298	134	0.379	2800	1
Pu-238	Alpha	0.56	19.86	0.39	87.48	300	15
Cm-242	Alpha	120	13.51	98	0.45	2000	1
Cm-244	Alpha	2.65	13.51	2.27	18.1	170	1
Tm-170	Beta	13.6	9.32	1.2	0.35	136	1
Ru-106	Beta	33.1	12.45	1.1	1	120	2.3
Pm-147	Beta	0.33	7.26	0.27	2.6	75	3.6

Table 3. Weighted scoring

	Particle Emitted	Specific Power	Density	Compound Specific Power (W/g)	Half-life	Cost	Availability (kg/100MweY)	Sum
Weighting factors	**0.05**	**0.03**	**0.02**	**0.3**	**0.25**	**0.25**	**0.1**	**1**
Sr-90	0.4	0.0020	0.0262	0.0049	0.7916	0.8125	0.4444	2.4817
Cs-137	0.15	0.0009	0.0344	0.0027	0.8573	2.5000	1.0000	4.5454
Po-210	0.5	0.3000	0.0936	3.0000	0.0108	0.0058	0.0278	3.9380
Pu-238	0.5	0.0012	0.2000	0.0087	2.5000	0.0542	0.4167	3.6808
Cm-242	0.5	0.2548	0.1361	2.1940	0.0129	0.0081	0.0278	3.1336
Cm-244	0.5	0.0056	0.1361	0.0508	0.5173	0.0956	0.0278	1.3331
Tm-170	0.4	0.0289	0.0939	0.0269	0.0100	0.1195	0.0278	0.7069
Ru-106	0.4	0.0703	0.1254	0.0246	0.0286	0.1354	0.0639	0.8482
Pm-147	0.4	0.0007	0.0731	0.0060	0.0743	0.2167	0.1000	0.8708

D. RADIOISOTOPE SELECTION

From the initial scoring, it was determined that the isotopes of Sr-90, Cs-137, Po-210, Pu-238, Cm-242, and Cm-244 are most effective for the given factors and deserve further analysis. To more effectively compare a potential radioisotope generator to current technology, it is necessary to determine the amount of material that will be necessary to provide useful power capabilities. For the purpose of this report, a useful energy of 300 Watts at an equipment lifetime of 10 years was used. System efficiency was disregarded at this point, due to large dependence upon the system thermoelectric materials.

The amount of material required to produce 300 W of energy at beginning of life (BOL), and after 10 years (EOL) was calculated, along with the estimated cost associated with the purchase of each isotope.

1. Strontium-90 (Example)

a. Pure Radioisotope Mass to Produce 300W Power

$$(300W)\left(\frac{gram}{0.96W}\right) = 312.5 \text{ grams}$$

b. Compound Mass to Produce 300W Power

$$(300W)\left(\frac{gram}{0.22W}\right) = 1{,}363 \text{ grams}$$

c. Estimated cost to Produce 300W power at BOL

$$(312.5g)\left(\frac{\$20}{g}\right) = \$6{,}250$$

d. Initial Pure Mass to Produce 300W Power at EOL

$$N_o = \frac{N(t)}{\left(\frac{1}{2}\right)^{t/t_{1/2}}} = \frac{312.5g}{\left(\frac{1}{2}\right)^{10\,yrs/27.7\,yrs}} = 401.4 \text{ grams}$$

e. Initial Compound Mass to Produce 300W Power at EOL

$$(401.4g)\left(\frac{1363g}{312.5g}\right) = 1751 \text{ grams}$$

f. Estimated Cost to Produce 300W Power at EOL

$$(401.4g)\left(\frac{\$20}{g}\right) = \$8,028$$

2. Estimated Cost and Weight Data

Table 5 was created using the methodology shown in the previous example for each potential radioisotope. The estimated cost and weight of compound needed to generate 300W of thermal energy at beginning of life was first calculated. Then, the estimated cost and weight of compound needed to produce 300W at the end of life (EOL) was calculated. In this case, EOL was assumed to be 10 years. Both steps are needed in order to effectively evaluate the material over a range of useful lifetimes.

Table 4. Initial cost and weight

Isotope	Pure isotope mass per 300W (g)	Compound mass per 300W (g)	Estimated cost per 300W ($)	Initial pure mass for 300W at EOL (g)	Initial compound mass for 300W at EOL (g)	Initial estimated cost for 300W at EOL ($)
Sr-90	313	1364	6250	401	1751	8027
Cs-137	714	2500	4642	900	3150	5850
Po-210	2	2	5945	186090003	196227741	521052007084
Pu-238	536	769	160714	580	833	173967
Cm-242	3	3	5000	12231943	14977890	24463887084
Cm-244	113	132	19245	166	194	28225

From Table 4, it can be observed that Po-210 and Cm-242 are unacceptable radioisotope choices for the proposed mission, due to their excessive cost and weight. The list of feasible radioisotopes for this application is limited to Sr-90, Cs-137, Pu-238, and Cm-244. Not surprisingly, the best choice radioisotopes have long half-lives and relatively low costs of production. These factors have been shown to be able to be used to easily eliminate infeasible solutions. The isotopes selected above should be reevaluated during system design, to determine feasibility with respect to other criteria, such as necessary system shielding.

The values above assume an unrealistic system efficiency of 100 percent, and were used only for the initial step of determining potential isotope feasibility. The actual cost and amount of compound required will be some larger amount. Further subsystem analysis will increase project fidelity by more accurately estimating both subsystem and total system efficiency.

IV. THERMOELECTRIC ELEMENTS

Though the radioisotope produces energy, this energy is emitted in the form of particles, which produce heat. For the application of providing power to a deployed unit, the form of energy needed is electricity. For this reason and explained below, it is necessary to utilize thermoelectric elements within the radioisotope power system. The major types of thermoelectric elements and their uses are summarized below.

1. Thermocouples

A thermocouple is a relatively simple device, consisting of dissimilar metals in physical contact with one another. When the conductors are subjected to a thermal gradient, a voltage is produced which is proportional to the temperature difference. In a power generation system, this voltage is used to measure temperatures of priority elements, ensuring that the generator is functioning properly.

2. Thermionic Converter

A thermionic converter is a static device that directly converts heat into electricity. This work is performed by heating one electrode to a very high temperature, while keeping another electrode a short distance away relatively cooler. Electrons from the hot electrode are vaporized and are condensed in the cooler electrode. The flow of electrons can be harvested if a load is attached to the converter.

As a type of Carnot engine, thermionic converters will have their ideal efficiency limited based upon the temperature of the electrodes. Electrode efficiency can be as high as 20 percent, with a high power density of up to 10 W/cm^2, but this operation occurs at very high temperatures, with the emitter at around 2000 K and the collector at around 1000 K (University of Wisconsin, 2000).

3. Alpha-voltaic Cells

Alpha-voltaic cells are composed of a semiconductor p-n junction diode that utilizes an alpha emitting source to generate electricity. Though alpha-voltaics have demonstrated relatively high efficiencies of around 20 percent, they are degraded by the impact of alpha particles, which degrades the output of the electrical cells (NASA, 2011). Prevention of this phenomenon must occur in order for the technology to be useful.

4. Beta-voltaic Cells

Operating similarly to alph-voltaics, beta-voltaics also consist of p-n junction type semiconductor material coupled to a beta radiation source. This directly converts energy from the beta source into an electrical output. Beta-voltaics are similarly degraded by the impact of beta particles, which degrades the output of the electrical cells, though not nearly as quickly as alpha-voltaics (NASA, 2011).

5. Thermophotovoltaic Cells

Thermophotovoltaic (TPV) cells directly convert heat to electricity using photons. The system consists of a thermal emitter and photovoltaic diode. The thermal emitter is a substance that emits photons. The diode is used to absorb the photons and create electricity. A standard solar cell is a form of a TPV generator, with the sun acting as the emitter.

6. Thermoelectric Power Component Selection

The thermoelectric material chosen is the primary factor determining the efficiency of the RTG. Research into these materials is ongoing, and it is an area of innovation, with new discoveries frequently being made, and higher efficiencies being produced.

The element efficiency (η) is defined as $\eta = \frac{\text{energy provided to the load}}{\text{heat energy absorbed at hot junction}}$. The efficiency of the device is directly related to its figure of merit, $ZT = \frac{\sigma S^2 T}{\lambda}$, where where S is the Seebeck coefficient, σ is the electric conductivity and λ is the thermal conductivity. Maximum theoretical device efficiency is limited by the difference in temperature between the hot and cold elements, as well as its figure of merit as,

$\eta_{\max} = \left[\frac{T_h - T_c}{T_h} \right] \left[\frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + 1} \right]$, where T_h and T_c are the temperature of the hot and cold sides, and $\overline{T}$ is the average of T_h and T_c (Chen, 2013, p. 4).

NASA's current version of RTG utilizes thermoelectric materials with a ZT of ~0.7, which corresponds to an efficiency of ~5 percent. Though this efficiency is sufficient for low power applications, it will probably not be suitable for use in a deployed unit, where size and weight is at a premium. It is necessary to select materials that are of higher efficiency. High performing compounds were thus analyzed.

The initial thermoelectric material selection is to be performed during the design process in a manner similar to that performed for the radioisotope. First, relevant data is to be gathered for possible compounds. Next, each compound will be ranked relative to a weighting system to determine overall suitability. Finally, potential materials should be reevaluated with respect to integration with other systems, such as the chosen radioisotope, as parameters such as operating temperature could greatly affect performance. It should be noted that, due to the immense amount of research into this area, future work should revisit this section in totality, to ensure that new, more effective elements are not being omitted. Additionally, ZT values given are those produced at the time of writing. Various research groups are making efforts to improve the efficiencies of known materials.

7. Initial Data

Table 5 shows the high and low measured effectiveness values for currently available thermoelectric materials.

Table 5. Figure of merit values of available thermoelectric materials

Compound	ZT (low)	ZT (high)
Silicon-Germanium	0.7	0.7
Bismuth chalcogenides	1	2
Lead telluride	1.4	1.8
Skutterudites	1	1
Half Heusler	0.5	1
Magnesium Group IV	0.9	0.9
Inorganic clathrates	0.7	1.7

8. Efficiency improvements

Though current ZT values are limited to around 2, corresponding to a unit efficiency of around 15–20 percent, these limits could change with upcoming research. By designing materials at the nanoscale and significantly reducing grain size, increases in efficiency of up to 40 percent have been realized in Bi-Te thermoelectrics. Further research into improving thermoelectric materials, most notable tellurides, could yield ZT values up to 3.0 in the near future, which would correspond to a unit efficiency of 20–30 percent.

V. RISK MANAGEMENT

1. Method

The risk management program for the project should be operated similarly to that specified in the risk management plan for DoD acquisition, with major steps performed as illustrated in Figure 5.

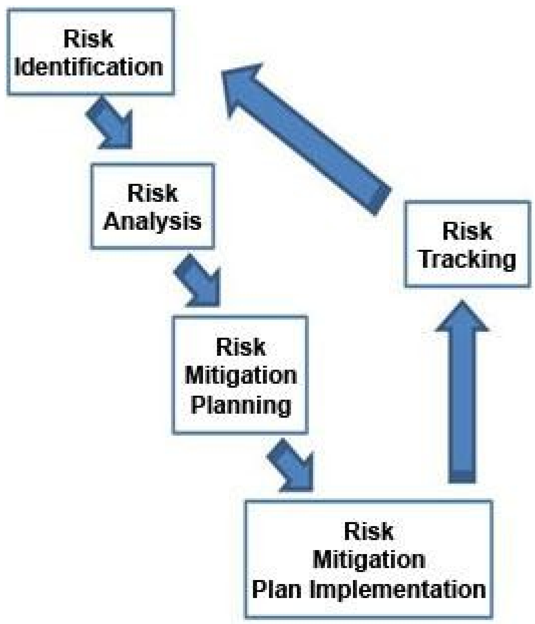

Figure 5. Risk management process (From Department of Defense, 2006, p. 4)

The initial step in the procedure is risk identification. For the purpose of this report, risk identification is performed as a top-down program level assessment. This must be performed as a part of the feasibility study to ensure that all program level risks can be mitigated to an acceptable level prior to completion of the design process. As final design elements are selected, risk identification will focus much more at the system and operational levels, seeking to identify additional risks associated with the physical elements of the system. For initial risk identification to be realistic and useful, stakeholder input will be gathered in order to gain multiple need based perspectives and to more effectively measure consequence.

As a part of the risk analysis step, each identified risk must be assigned one or more future root causes, classified into type, and assigned a likelihood and consequence level (Department of Defense, 2006, pp. 7–9). The risk reporting matrix shown in Figure 6 will be utilized to perform this step, so that various risks can be easily visualized and prioritized.

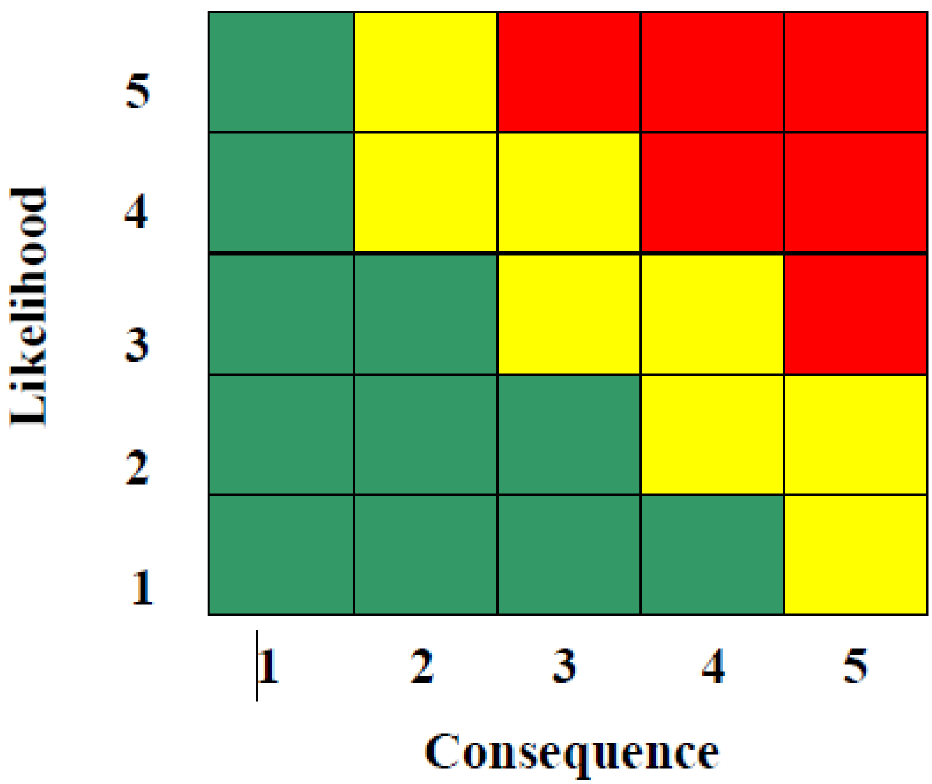

Figure 6. Risk reporting matrix (From Department of Defense, 2006, p. 11)

For the preliminary planning, the DAU definitions shown in Figures 7 and 8 should be used to rank each identified risk.

Likelihood

Level	Likelihood	Probability of Occurrence
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

Figure 7. Levels of likelihood criteria (From Department of Defense, 2006, p. 12)

Consequence

Level	Technical Performance	Schedule	Cost
1	Minimal or no consequence to technical performance	Minimal or no impact	Minimal or no impact
2	Minor reduction in technical performance or supportability, can be tolerated with little or no impact on program	Able to meet key dates. **Slip < _*_ month(s)**	Budget increase or unit production cost increases. **< _**_ (1% of Budget)**
3	Moderate reduction in technical performance or supportability with limited impact on program objectives	Minor schedule slip. Able to meet key milestones with no schedule float. **Slip < _*_ month(s)** **Sub-system slip > _*_ month(s) plus available float.**	Budget increase or unit production cost increase **< _**_ (5% of Budget)**
4	Significant degradation in technical performance or major shortfall in supportability; may jeopardize program success	Program critical path affected. **Slip < _*_ months**	Budget increase or unit production cost increase **< _**_ (10% of Budget)**
5	Severe degradation in technical performance; Cannot meet KPP or key technical/supportability threshold; will jeopardize program success	Cannot meet key program milestones. **Slip > _*_ months**	Exceeds APB threshold **> _**_ (10% of Budget)**

Figure 8. Levels and types of consequence criteria (From Department of Defense, 2006, p. 13)

The next step of the procedure is risk mitigation planning. This involves the creation of a strategy to minimize the likelihood or consequence of each identified risk, and a reevaluation and ranking of the risk after imposing mitigation procedures. The iterated values are graphed on another risk matrix in order to perform final analysis.

Risk mitigation plan implementation refers to the design team taking steps to mitigate identified risks. These are the physical actions that are performed.

The final step in the procedure is risk tracking. This step is performed to identify changes in the product over time, and to identify new or previously unknown risks. Proper risk tracking involves a log of how identified risks are actually affecting the system, so that they can be reevaluated.

The risk process is necessarily iterative. It will generally not be possible to identify all applicable risks prior to fielding the technology, so periodic evaluation of the program will be utilized to ensure all risks are being handled properly.

2. Barriers to Implementation

a. Medical

Producing energy from a radioisotope, an RTG must emit some amount of radioactive elements. These elements have the potential to interact with the human body in numerous ways, increasing the risks of medical issues such as cancer. While the specific medical risks are dependent upon many RTG factors, such as the specific radioisotope chosen, and the type and amount of shielding utilized, in all cases, the medical risks posed from radiation must be considered.

As a generator of heat, the RTG would also pose a burn risk to personnel, or could even generate temperatures high enough to damage the equipment itself. Though a cooling system has been identified as a necessary subsystem, the subsystem must be integrated to the point of providing cooling during times of RTG non-operation, such as during transport and setup.

b. Environmental

Similar to medical risks, radiation emitted from the power element can interact with other environmental objects. An uncontrolled release of radiation could damage the environment for an extended period of time. Certainly, this would not be acceptable. Public opinion objection alone would stop this.

c. Cooling

As the generator will not be 100 percent efficient, it must be designed with the ability to reject excess heat in some manner, to prevent damage to the equipment. Simple radiative heat transfer to the surrounding environment may not provide enough cooling, necessitating the design of an integrated cooling subsystem. Previously used RTG architectures have included a cooling system, powered by the RTG itself to reject excess heat. As the USMC mission characterization includes providing power to a mobile, deployable force, the RTG must possess the ability to reject unused heat energy in all states: while deployed, during storage, and during transport. This could involve the design of an always operable cooling subsystem.

d. Cost

Though RTG technology has been utilized for decades and is proven, the technology has never been used in such a way as to power an operational deployed unit previously. The power requirements for such a unit could prevent the technology from being fiscally feasible, which would doom the study.

e. Performance

Similar to cost, it is possible that RTG technology will simply be insufficient to meet any military needs. The consequence of this would be the end of the study.

f. Public Perception

Public perception must be considered in the design of this technology. With the ever-growing sentiment that the military must be transparent to the taxpayers, it is likely that fringe groups opposing nuclear technology will lobby against its development and use. It is also likely that the military personnel using the technology will be uncomfortable with it, or not trust the equipment. These emotions should be surveyed and included in the design process, to ensure that time and resources are not wasted developing a technology that will not be accepted by the public.

g. Foreign Laws

If the technology is used for its intended purpose, it will likely be used in foreign countries all over the world. Foreign regulations regarding nuclear power must be studied to ensure that the military is not operating outside of the bounds of the law. If it is found that RTG technology is illegal in proposed operating locations, it could reduce the feasibility of producing the generator.

h. Battle Damage

It will be possible to choose RTG shielding that will minimize the amount of radiation encountered by users of the generator. Shielding can be selected that will pass only a negligible amount of radioactive particles outside the RTG, such that health effects will be non-existent. There will be a risk, however, of the RTG taking battle damage. If the generator is subjected to physical shock, such as from an enemy projectile or blast weapon, it is possible that it could develop holes, or suffer a loss of shielding. This could expose personnel to radioactive elements, increasing their chances of suffering negative health effects. This can be mitigated by hardening the system. Though the danger from the enemy weapons would likely dwarf that from the radioisotope, it is nevertheless a risk that must be fully examined during the design stage. Prevention of this casualty would likely come from case hardening the vessel, providing shock shielding, or utilizing the RTG in environments with minimal risk of attack. The most effective troop safety measure for this hazard however, is already in place. Troops are trained in the proper actions to take in the event of a chemical, biological, radiological, or nuclear (CBRN) attack, and, in instances where the attack is likely, carry protective equipment such as gas masks, which would help prevent particle inhalation.

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VI. CONCLUSIONS

A. KEY POINTS

Large steps must be taken with regard to reduction of fuel usage for the USMC and E2O to reach their energy goals in the coming years. If the usage of RTG technology is to be a factor in the military's energy plan, it is in the best interest of all stakeholders to determine the potential of the system early, so that potential uses can be explored prior to system development. This report has shown that, with regard to power production capability, and size and weight considerations, RTGs are a feasible source to bridge the power gap between large generators and smaller batteries.

It was seen that the effectiveness of the technology depends upon the continued development of energy conversion equipment, a field that must continue to be driven in order to take advantage of new improvements.

B. RESEARCH CONCLUSIONS

1. Utilizing RTG power to provide energy to deployed units is a feasible concept. The most suitable radioisotopes to make use of are Strontium-90, Cesium-137, and Curium-244, due to their combination of fuel characteristics.
2. Radiation shielding is less of a concern than previously thought, due to the tendency for suitable radioisotopes to emit primarily non-penetrating radiation.
3. Appropriate system hardening can be developed if deemed necessary.
4. Health hazards are less of a concern than previously thought, due to the tendency for suitable radioisotopes to emit primarily non-penetrating radiation. The potential for health damage to occur is therefore limited to effects following the destruction of the generator.
5. Feasible thermoelectric elements currently exist, most notably created as compounds of lead telluride, the best of which would lead to an estimated system efficiency of 10 percent.
6. The status of current thermoelectric research is such that near-term major advances will possibly make currently available elements obsolete. Thermoelectric research must be constantly reevaluated during the design process to make use of newly available technology.

C. FURTHER RESEARCH

Future research into the use of RTG technology would do well to focus on a number of key areas.

Subsystem feasibility should continue to be evaluated in order to determine the most effective physical component types for each subsystem. Each component identified will increase the model fidelity by allowing a more effective estimation of overall performance and cost estimation. Radioisotope health and environmental effects, as well as controls criteria should be reevaluated with respect to usability and product restrictions.

Operational system architecture should continue to be detailed. Further decomposition should focus on subsystem interrelations and identification of key objects. This will help to ensure complete analysis prior to the design phase of the project. System architecture should be further decomposed to ensure that a constant system power output can be obtained throughout all potential usage types.

Stakeholder analysis should be reevaluated and continued. If possible, additional primary stakeholders should be incorporated into the project, so that research costs and ideas can be shared.

The analysis models should continue to be developed, including possible variations to the weighting factors utilized, based upon stakeholder input. Additional physical possibilities should be researched and described to ensure that prospects are not disregarded prematurely.

The initial processes should be reevaluated in an iterative process. As subsystems are further defined, previously identified components should be evaluated with respect to overall system integration.

An RTG prototype should be developed and tested in a real-world scenario in order to validate the design process and verify its functionality.

D. SUMMARY

The need to reduce battlefield fuel consumption is very real. In order to meet the E2O mission goal of maintaining structural systems powered without using fossil fuels will require innovation in a number of different areas of alternative energy. This report has shown that radioisotope thermoelectric generators have the potential to provide a constant, stable portion of this power demand, and could help to achieve a total power system if paired with other types of energy production equipment. The possibility also exists that the technology could be used for other mission areas within the military complex, such as acting as a power source for unmanned equipment. Further research into the technology is needed to determine a feasible operational concept. A focus on partnership amongst services could help to more effectively share information and development, and should be explored fully.

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LIST OF REFERENCES

Chen, R. (2013, April 17). Silicide nanopowders as low-cost and high-performance thermoelectric materials. TMS.

Defense Acquisition University. (2012, November 15). *Systems Engineering Process.* Retrieved from ACQuipedia Web site: https://dap.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=9c591ad6-8f69-49dd-a61d-4096e7b3086c

Department of Defense. (2006, August). *Risk management guide for DoD acquisition.* Retrieved from https://acc.dau.mil/CommunityBrowser.aspx?id=108780

Dworschak, M. (2006, December 05). *The Ideal Poison: Where Polonium Comes From*. Retrieved April 02, 2013, from http://www.spiegel.de/international/spiegel/the-ideal-poison-where-polonium-comes-from-a-452706.html

Environmental Protection Agency. (2012a, July 26). *Alpha Particles*. Retrieved March 06, 2013, from http://www.epa.gov/radiation/understand/alpha.html

Environmental Protection Agency. (2012b, April 24). *Americium*. Retrieved April 8, 2013, from http://www.epa.gov/radiation/radionuclides/americium.html#affecthealth

Environmental Protection Agency. (2012c, March 6). *Cesium*. Retrieved April 9, 2013, from http://www.epa.gov/radiation/radionuclides/cesium.html#affecthealth

Environmental Protection Agency. (2012d, March 6). *Plutonium*. Retrieved April 8, 2013, from http://www.epa.gov/radiation/radionuclides/plutonium.html#affecthealth

Environmental Protection Agency. (2012e, April 24). *Strontium*. Retrieved April 8, 2013, from http://www.epa.gov/radiation/radionuclides/strontium.html#affecthealth

Govar, C. (2011, May 5). *Marine corps renewable energy and microgrid efforts.* Retrieved from Defense Technical Information Center Web site: http://www.dtic.mil/ndia/2011power/Session8_12081Govar.pdf

ICRP. (1991). *1990 Recommendations of the international commission on radiological protection.* Retrieved from ICRP Publication 60: http://www.icrp.org/publication.asp?id=ICRP%20Publication%2060

International Atomic Energy Agency. (2013). *Polonium-210*. Retrieved April 02, 2013, from http://www.iaea.org/Publications/Factsheets/English/polonium210.html

Marine Corps Expeditionary Energy Office. (2011). *United States Marine Corps expeditionary energy strategy and implementation plan.* Washington, DC.

NASA. (2011, September 28). *Alpha- and beta-voltaics.* Retrieved from Glenn Research Center Web site: https://rt.grc.nasa.gov/power-in-space-propulsion/photovoltaics-power-technologies/technology-thrusts/alpha-and-beta-voltaics/

National Air and Space Museum. (1999, July). *SNAP-27*. Retrieved February 5, 2013, from http://solarsystem.nasa.gov/rps/rtg.cfm

Rumyantsev, A. Y. (2003). *International cooperation in the field of safe and secure use of ionizing radiation sources.* Retrieved from http://www.iaea.org/newscenter/features/radsources/statement_rus.pdf

U.S. Navy. (2006, November 28). *Navy organization.* Retrieved from A U.S. Navy Web site: http://www.navy.mil/navydata/organization/org-shor.asp

United States Nuclear Regulatory Commission. (2012, October 3). *Fact sheet on Polonium-210.* Retrieved April 9, 2013, from U.S. NRC: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/polonium.html

University of Wisconsin. (2000, Spring). *Thermionic energy conversion*. Retrieved from http://fti.neep.wisc.edu/neep602/SPRING00/lecture9.pdf

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