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Replacing ^{238}Pu in Radioisotope Power Systems

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May 8, 2012

Abstract

The isotope ^{238}Pu is no longer available for use as a power source for NASA space probes, and an alternative must be found. The α-decay of ^{238}Pu once powered both radioisotope thermoelectric generators and radioisotope heater units, which provide electricity and heat, respectively, to the probes' instrumentation. This study investigates the viability of seven radioisotopes similar to ^{238}Pu into integration with the same components. Using the Cassini space probe mission standards as a model, this work considers the power output, half-life, mass, and safety factors of each potential power source. Three of the initial seven isotopes in consideration outperformed ^{238}Pu in both the Cassini mission-specific model and more general models with various mission lengths and fuel masses. ^{250}Cf, ^{244}Cm, and ^{243}Cm provided more power yet used a smaller fuel mass than ^{238}Pu. They also fulfilled many of the same safety criteria required of ^{238}Pu, such as undergoing alpha decay almost exclusively, decaying into other alpha-emitters, and forming ceramic oxides. The best performer, ^{250}Cf, had a higher specific power than ^{238}Pu for mission lengths up to 44 years. NASA missions have been cancelled due to the scarcity of ^{238}Pu, but a radioisotope that fulfills all of the same power, mass and safety criteria could salvage the missions.

1 Introduction

1.1 Motivation

NASA's space probes that use a radioactive isotope, or radioisotope, as their power source are much more versatile than probes that rely on the sun. Solar panels only work in direct, high-intensity sunlight— up to the distance of Mars' orbit from the sun. But *Voyager 1*, launched in 1977 and the farthest human-made object from the sun at 18 billion kilometers, continues to operate. The slow but continuous decay of its radioisotope releases heat, which is converted into usable electricity. [10] NASA exclusively uses ^{238}Pu to power space probes, but has consumed all available supplies and, due to a confluence of political factors, cannot get any more.

According to a NASA statement explaining the choice of ^{238}Pu for the Cassini mission to Saturn,"In principle, any radioisotope with a half-life long enough to provide sufficient power throughout the Cassini mission and with a high enough specific activity to provide the required power with a suitably small generator can be used." [2] This document was originally written for Cassini but can be applied to other missions, too. As NASA delays or cancels future exploration missions relying on ^{238}Pu, this study seeks other radioisotopes that could fulfill the same mission power requirements and therefore replace the ^{238}Pu. Since NASA has already spent decades of research designing safe radioisotope power system (RPS) equipment, the purpose of this study is to find isotopes that will be compatible with the existing RPS and be of comparable cost to and greater availability than ^{238}Pu.

1.1.1 ^{238}Pu Usage in History

Since 1961, ^{238}Pu has produced heat or electricity for 31 NASA missions with a wide variety of mission sizesw, goals, and destinations, with great success. [17, 7] Listed in Table 1, the missions range from weather satellites orbiting Earth, to research equipment on the moon, to deep space probes. (The gap in missions between 1977 and 1989 is mainly due to mission delays following the *Challenger* disaster.) Clearly, ^{238}Pu is easily adaptable and its continued use for over 50 years shows NASA's dedication to the technology.

1.1.2 Causes of Current ^{238}Pu Shortage

The United States once produced its own ^{238}Pu by bombarding ^{237}Np with neutrons at the Department of Energy's (DOE) Los Alamos National Laboratory. The DOE works with NASA to supply the ^{238}Pu for its scientific missions. A security incident at Los Alamos involving missing classified computer disks shut down production in 1988 and it never restarted. [18] Subsequent missions relied on existing ^{238}Pu stockpiles, and in 1992 the DOE negotiated a trade agreement with Russia so it would supply the U.S. with some of its own stock as well. [19] In general, thes combined stockpiles are leftover from decommissioned nuclear missiles from the Cold War. While ^{238}Pu can be extracted from milliwatt power systems on the nuclear missiles, most has either been extracted already or the radioactive fuel has decayed away. [19] In 2009, Russia's Rosatom State Atomic Energy Corporation chose not to uphold the trade agreement, intending to renegotiate for a higher price, which the DOE has refused to pay. [20]

In 2005, the DOE announced its intentions to restart production of ^{238}Pu by 2011 at the Idaho National Laboratory. [19] All subsequent requests by both the DOE and NASA to obtain the necessary Congressional funding have been unsuccessful. Each year the two agencies submit budget requests for the ^{238}Pu production funding, but at least one House in Congress always refuses. [15]

1.1.3 Effects of Current ^{238}Pu Shortage

Due to the lack of radioisotope fuel, intended probe missions have been cancelled, delayed, or downsized to accomodate solar panels. Launched in 2006 after the fuel shortage began, the New Horizons mission actually lacked sufficient ^{238}Pu for its mission requirements. [18] And the Mars Science Laboratory Rover, launched in 2011, consumed the last of NASA's ^{238}Pu stockpiles. Many planetary and deep space researchers are currently being forced to change their specialties and research proposals because scientific missions to within the asteroid belt that could use solar panels are far more likely to receive funding than missions to the outer planets. Delaying or cancelling missions that rely on RPS creates a loss of highly skilled and specialized jobs, and threatens American dominance in space exploration and research. Even if the DOE restarted production today, it would take nearly a decade to reach the level of ^{238}Pu production that NASA needs: about 2 kg annually. [23] A solution must be found immediately in order to minimize delays and return to the original schedule of missions.

Launch Year	Spacecraft	Type of Power System
1961	Transit 4A	SNAP-3B
1961	Transit 4B	SNAP-3B
1963	Transit 5BN-1	SNAP-9A
1963	Transit 5BN-2	SNAP-9A
1963	Transit 5BN-3	SNAP-9A
1969	Nimbus-B	SNAP-19B
1969	Nimbus-III	SNAP-19B
1969	Apollo 11	RHU
1969	Apollo 12	SNAP-27
1970	Apollo 13	SNAP-27
1971	Apollo 14	SNAP-27
1971	Apollo 15	SNAP-27
1972	Pioneer 10	SNAP-19
1972	Apollo 16	SNAP-27
1972	Transit TRIAD	Transit-RTG
1972	Apollo 17	SNAP-27
1973	Pioneer 11	SNAP-19
1975	Viking Mars Lander 1	SNAP-19
1975	Viking Mars Lander 2	SNAP-19
1976	LES 8	MHW-RTG
1976	LES 9	MHW-RTG
1977	Voyager 2	MHW-RTG
1977	Voyager 1	MHW-RTG
1989	Galileo	GPHS-RTG
1990	Ulysses	GPHS-RTG
1996	Mars Pathfinder - Sojourner	RHU
1997	Cassini-Huygens	GPHS-RTG; RHU
2003	Mars Exploration Rover - Spirit	RHU
2003	Mars Exploration Rover - Opportunity	RHU
2006	New Horizons	GPHS-RTG
2011	Mars Science Laboratory Rover	MMRTG

Table 1: NASA missions with ^{238}Pu fueling its power systems, by launch date. SNAP is an acronym for Systems for Nuclear Auxiliary Power, MHW for Multi-Hundred Watt, GPHS for General-Purpose Heat Source, and MM for Multi-Mission, all types of RTGs.

1.1.4 Possible Alternative Sources of ^{238}Pu

Few alternative sources of ^{238}Pu exist. The European Space Agency (ESA) is considering its own production of plutonium “to support joint NASA-ESA programs” but it is unclear if it currently has the facilities to do so. [26] The isotope is too rarely found in nuclear power plant waste for the expense of its extraction to be worthwhile. There is a possibility that it could instead be extracted from the Hanford Site, a federal nuclear production facility in Washington state, starting in the 1940s. Now closed due to contamination, the facility's inventory includes over 4,000 kilograms of plutonium. [14] The inventory does not reveal the abundance of each plutonium isotope; however, it is most likely primarily ^{239}Pu rather than ^{238}Pu. The facility produced weapons-grade fuel (which is mostly ^{239}Pu) and ^{239}Pu has a much longer half-life than ^{238}Pu.

1.2 Research Objectives

This work endeavors to find radioisotopes that fulfill general NASA mission standards and are more readily available than ^{238}Pu. Ideally they would replace ^{238}Pu in the heating and electrical components with little modification to the current RPS. According to NASA's Jet Propulsion Laboratory, which oversees most of the exploration missions,

> To be suitable for space missions, a radioisotope must meet all of the following criteria:[9]
>
> - Exist in an insoluble form and/or otherwise not be readily absorbed into the body in the unlikely event of a launch accident
> - Exist in a form such that it presents no or minimal chemical toxicity when taken into the body
> - Have relatively low neutron, beta and gamma radiation emissions, so as to not adversely affect spacecraft instruments or require excessively massive shielding
> - Be stable at high temperatures, so its characteristics remain essentially unchanged over many years
> - Have a long enough half-life (at least 15 to 100 years), so that it can generate for many years sufficient heat for transformation into electricity
> - Have a high power density, so a small amount of it can generate a substantial amount of heat

This paper addresses the third, fifth, and sixth points but the half-life criterion will be expanded to include half-lives ranging from 5 years to 1000 years, i.e. about a factor of ten decrease and increase from ^{238}Pu's 87.7 year half-life.

A successful alternative radioisotope will provide enough energy to fulfill the mission's heating or power requirements at both the beginning and end of the intended mission timeframe. It should act similarly to ^{238}Pu: it must also undergo alpha decay, release a similar amount of energy in the process, and have a similar half-life and mass. As the replacement radioisotope would also emit alpha particles, the same safety regulations for ^{238}Pu would apply to the new isotope or would require little modification. The type and activity of its decay products must also be taken into consideration. As a precaution, the radioisotope should be able to form a ceramic oxide or a similar chemical structure to safeguard against its vaporization in the event of an accidental atmospheric re-entry. The cost of a NASA mission is heavily dependent on the payload weight so a low-weight power source is highly preferred.

This study intends to answer three research questions.

1. Which radioisotope fuels provide more power for less mass and/or less volume than ^{238}Pu and therefore ought to be considered in the development and design of future power systems from scratch?

2. Which fuels would be appropriate alternatives to ^{238}Pu in a RTG model currently in use, based on mass and volume limitations and the Cassini mission's power requirements?

3. Which fuels would be appropriate alternatives to ^{238}Pu in a RHU model currently in use, based on mass and volume limitations and general mission power requirements?

1.3 Related Work

Highly efficient RPS that require much less ^{238}Pu than previous models are currently in the testing phase but they still need *some* fuel to work. ESA is investigating using ^{241}Am in RPS since it can be easily harvested from smoke detectors. [5] However, it has longer half-life and smaller energy output than ^{238}Pu and requires more shielding because it emits neutrons, not alpha particles. ^{90}Sr and ^{233}Cm have also been identified for use in RTGs, but "neither oxide has a significant environmental advantage over plutonium dioxide", both emit γ-radiation that would require extensive shielding both before and during the mission, and the production facilities do not exist to produce either one in sizeable quantities. [2]

2 Background

2.1 Radioactive Decay

2.1.1 Atomic Instability

A nucleus undergoes energetically favorable decay routes, as determined by the separation energy of that decay type or the energy state of the nucleus. The separation energy is equal to the difference in binding energies of the parent nucleus (Equation 1) and of the daughter nucleus and emitted particle(s). The separation energy must be negative in order for the process to be energetically favorable, and is the negative of the energy released. The energy that is released is transferred into the large kinetic energy of the small, emitted particle and the much smaller kinetic energy in the recoil of the daugher nucleus.

The binding energy is the difference in mass-energy of the bound nucleus and its unbound components,

$$B(Z, N) = c^2(Zm_p + Nm_n - m(Z, N)), \tag{1}$$

where $B(Z, N)$ is the binding energy of an atom with Z protons and N neutrons,, m_p is the proton mass, m_n is the neutron mass, and $m(Z, N)$ is the mass of the bound nucleus. The binding energy equation ignores the binding energies of the atom's electrons because they are about 10^6 times smaller than the nuclear ones. [25]

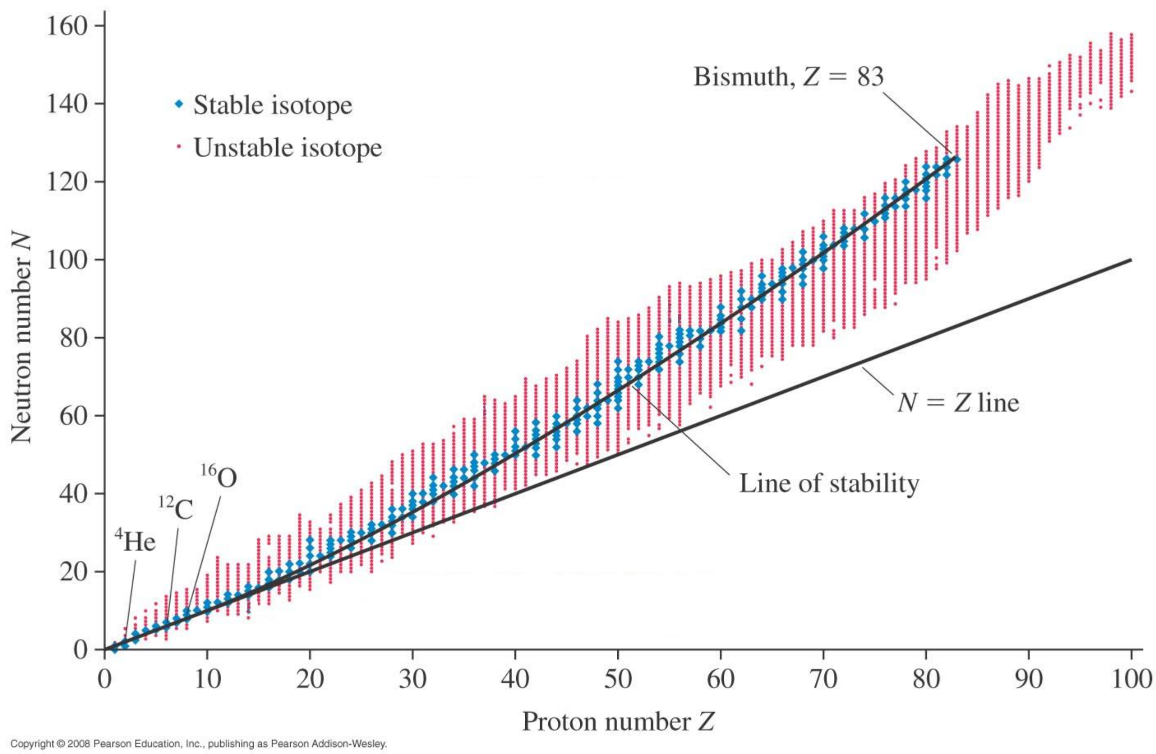

Figure 1: Stable and unstable nuclei shown on a plot of neutron number N versus proton number Z. Unstable nuclei are in bands along both sides of the line of stability. [25]

2.1.2 Decay Types

This study focuses on α-decay but a brief explanation of the three main decay types is included. Atoms of any size may undergo β-decay or γ-decay but most atoms with more than 150 nucleons are unstable and will undergo α-decay to reach a more stable configuration. [21] The main cause of such instability is the interaction of attractive strong forces between the nucleons and repulsive Coulomb forces between the protons. Figure 1 shows the stable isotopes in blue and unstable ones in red. A γ-ray is generally higher energy than the α-decayprocess, which releases more energy per decay than β-decay.

If the atom has too many protons and/or neutrons, it may undergo α-decay (Equation 2) in which the parent nucleus emits an α-particle, a helium nucleus composed of two protons and two neutrons.

$$^{\mathrm{A}}X_{\mathrm{Z}} \rightarrow {}^{\mathrm{A\text{-}4}}Y_{\mathrm{Z\text{-}2}} + \alpha + E \tag{2}$$

$^{A-4}Y_{Z-2}$ is the daughter nucleus, α is the α-particle and E is the energy released in the process. α-particles are relatively large and ionized with a +2 charge so they have the shallowest penetration depths in matter and a penetration length of several centimeters in air. α-particles cannot even penetrate a sheet of paper, which means little shielding is necessary to protect both nearby humans and delicate instruments. Their large kinetic energy and mass causes them to inflict significant physical damage to the barrier, though. [25]

If the atom has too many neutrons, it may undergo β^{-}-decay (Equation 3) in which one of its neutrons changes into a proton and an electron (thus charge is conserved). The nucleus emits the electron, energy, and an antineutrino, the latter ensures mass-energy is conserved.

$$^{\mathrm{A}}X_{\mathrm{Z}} \rightarrow {}^{\mathrm{A}}Y_{\mathrm{Z+1}} + e^{\text{-}} + \bar{\nu} + E \tag{3}$$

$^{A}X_{Z}$ is the parent nucleus, $^{A}Y_{Z+1}$ is the daughter nucleus, e^{-} is an electron, and $\bar{\nu}$ is an anti-neutrino.

If the atom has too many protons to keep the two forces balanced, it may undergo β^{+}-decay (Equation 4) in which one of its protons changes into a neutron and a positron; and the positron, a neutrino, and energy are emitted.

$$^{A}X_{Z} \rightarrow {}^{A}Y_{Z-1} + e^{+} + \nu + E \tag{4}$$

$^{A}Y_{Z-1}$ is the daughter nucleus, e^{+} is a positron, and ν is a neutrino. Both types of β-decay have intermediate penetration depths and cause some kinetic damage so they require significant shielding. [25]

If the atom is in an excited state, it may undergo γ-decay to release a high-energy photon (Equation 5) in order to return to the energetically-preferable ground state. γ-raydoes not decay into another nucleus, just into a less excited state of the same atom. It has the highest penetration and lowest ionization and requires the most extensive shielding by far. [25]

$$^{A}X_{Z}[excited] \rightarrow {}^{A}X_{Z}[ground] + E \tag{5}$$

2.1.3 Decay Mechanics

The change in the number of atoms over the time interval dt is

$$dN(t) = -\lambda N dt \tag{6}$$

where dN(t) is the change in the number of unstable atoms, lambda is the probability of decay, N is the number of atoms that can decay, and the negative sign denotes that the number of atoms is decreasing. Dividing both sides by the time interval to find the activity and integrating to find the number of atoms at a given instant,

$$\frac{dN(t)}{dt} = -\lambda N = -A(t) \tag{7}$$

$$N(t) = N_0 e^{-\lambda\, t} \tag{8}$$

The decay constant lambda is related to the isotope's half-life. By definition, half of a sample of atoms will have decayed after one half-life has elapsed.

$$N(t_{\frac{1}{2}}) = N_0 e^{-\lambda\, t_{\frac{1}{2}}} = \frac{1}{2} N_0 \tag{9}$$

Therefore,

$$e^{-\lambda\, t_{\frac{1}{2}}} = \frac{1}{2}$$

$$-\lambda\, t_{\frac{1}{2}} = ln\frac{1}{2}$$

$$\lambda = \frac{ln2}{t_{\frac{1}{2}}} \tag{10}$$

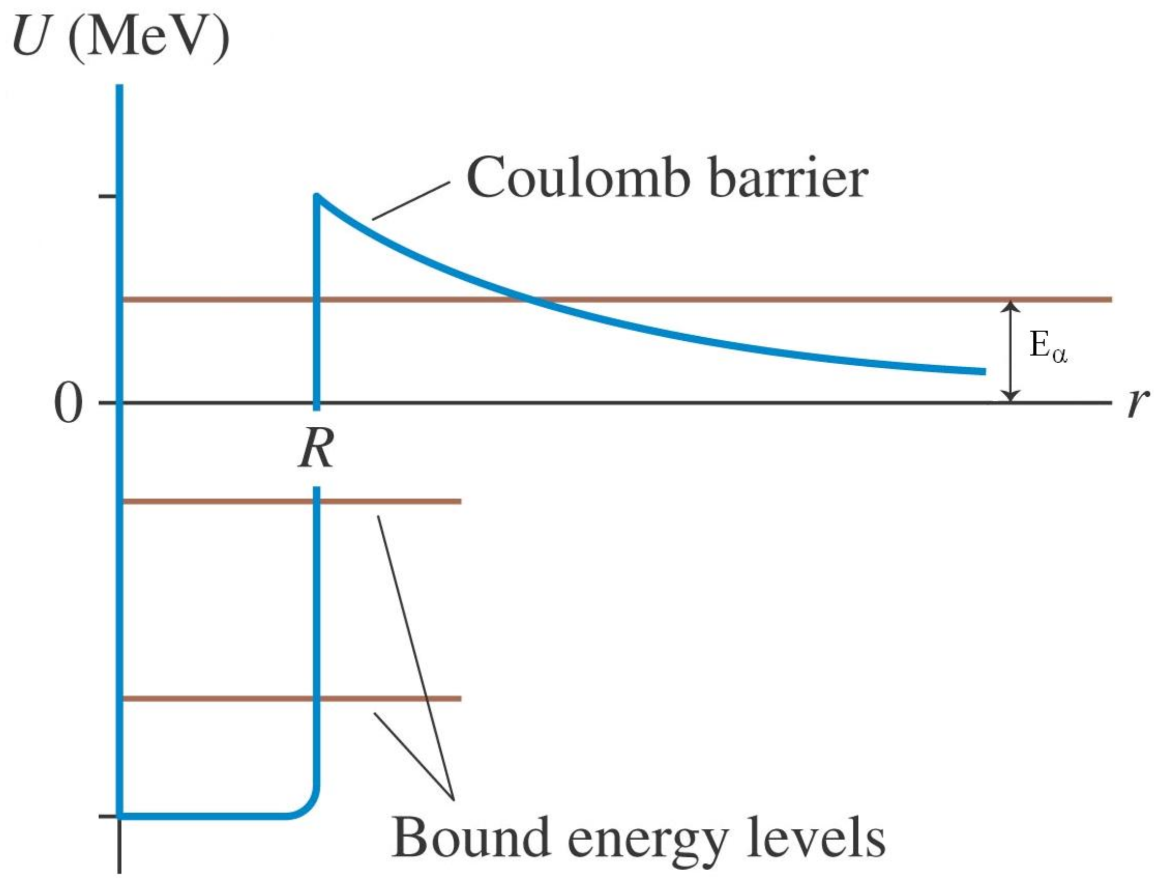

Figure 2: Potential barrier for an α-particle inside the nucleus. The α-particle has potential energy E_α inside the nucleus which is transformed into kinetic energy E_α outside the nucleus. [25]

2.2 Ceramic Oxides

An element's oxidation states are determined by its electron configuration. Multiple oxidation states are possible depending whether the atom would rather gain or lose electrons until the outermost electron shell is full or empty, respectively, or spread the electrons around its topmost shells. It is most energetically favorable for the atom to have complete electron shells. The oxidation state is a positive number if its outermost shell has that number of electrons it is willing get rid of in order to empty that shell. The oxidation state is a negative number if its outermost shell lacks that number of electrons to be complete.

In an ionic bond, one atom's superfluous electrons are donated to another atom so both have more complete electron shells and, now oppositely charged ions, the atoms attract and bond. All metals, which includes the isotopes in this study, bond ionically. To form a metal oxide, a metal donates its outermost electrons to oxygen atoms until both have complete or at least energetically preferrable electron shells. The metal must be heated in the presence of oxygen (a redox reaction) for the process to occur.

The ^{238}Pu in RPS fuel is in the form of a ceramic oxide as a safety precaution against its dispersal after severe destruction of the radioisotope casing from an accidental atmospheric re-entry. The event is highly unlikely but serious enough to warrant safeguards.

2.3 Radioisotope Power Systems

Unlike solar panels, a radioisotope produces power even at great distances from the sun or not directly facing it. ^{238}Pu is especially well-suited for long, unmanned missions because it provides a steady amount of power for decades and it can power systems without moving parts, which would eventually break down or require maintenance. Radioisotope power systems (RPS) are divided into radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs), which are designed to provide electricity and heat, respectively, to instrumentation on spacecraft.

2.3.1 Radioisotope Thermoelectric Generators

RTGs are a type of RPS that convert the heat released by the decay of plutonium into DC electricity that will power a space probe's instrumentation. This generation of electricity relies on the Seebeck effect: two dissimilar metals joined in a loop with the two junctions at different temperatures create a voltage difference between the two and cause an electric current through the circuit. [12] The circuit formed by the two metals is called a thermocouple. On Cassini and other spacecraft, one junction is in thermal contact with the decay heat from the RTG modules (about 1300 K with plutonium fuel) and the other is exposed to the cold of space. [27] The larger the temperature gradient, the greater the voltage potential created between the two regions of differing temperatures. Thermocouples are connected in series to increase the total voltage available and compose a thermopile.

Over time RTGs lose efficiency because the temperature gradient decreases over time. As the radioisotope decays away, there are fewer decays and less energy is released in a given time interval. The RTG produces less heat so its side of the thermocouple junction is less hot while the temperature of space on the other side remains constant. The smaller temperature difference reduces the amount of electricity that can be generated. In addition, the thermocouples will degrade from their already-low starting efficiency of 6.5%. [16]

Although RTGs are inefficient, they are also highly reliable. They lack moving parts that can break down or require servicing. Unmanned planetary probes are never intended to return to Earth so it is impossible to replace any equipment that fails during the mission. Voyager 1, launched in 1977 and now the farthest man-made object from the sun, is still functioning because it uses an RTG power source. [10] RTGs can function in the very extreme conditions of space- very far or close to the Sun and anywhere in between. In this regard, RTGs are much more versatile sources of electricity than solar panels. Solar panels only work where sunlight is neither too strong nor too weak for the sensitive devices, between about Venus' and Mars' orbits.

Since RTGs are so useful in space, the DOE has developed several models. The model of the three RTGs used on the *Cassini* spacecraft is the General Purpose Heat Source (GPHS) RTG. [2] The GPHS-RTG is 114 cm long x 42 cm in diameter, has a mass of 56 kg, and has two main parts: the fuel source and a thermoelectric converter to convert the fuel's heat into electricity. [2] An RTG's thermoelectric converter is composed of 572 silicon germanium (SiGe) thermocouples. [2] The fuel source is highly compartmentalized for safety precautions: If one pellet is compromised, only a small amount (150 g) of radioactive fuel may be exposed. There are 18 iridium-clad fuel modules per RTG, and each module contains four ^{238}Pu fuel pellets. [24] The fuel pellet is about the size and shape of a marshmallow. At launch the RTG is designed to provide 285 watts electric from 4,264 watts of heat. [2]

2.3.2 Radioisotope Heater Units

RHUs are a type of RPS that directly applies the heat from radioactive decay to surrounding instrumentation in order to keep them within their operating temperature ranges. The model currently in use is the lightweight RHU (LWRHU, or RHU, for short). Each one has a mass of 40 g, measures 3.2 cm long by 2.6 cm in diameter and produces about 1 thermal watt. [8] RHUs use plutonium dioxide as the radioactive fuel, which is enriched to 83.50% ^{238}Pu by weight at launch. [27] RHUs are particularly useful for spacecraft that cannot rely on solar energy to sufficiently heat components. The low intensity of sunlight at Saturn rules out solar energy as a heating option for Cassini so it used 117 RHUs instead.

Unlike RTGs which are placed at one end of Cassini and shielded to minimize disruption to the instrumentation, RHUs are spread strategically around the spacecraft to directly heat the components. Radioisotope heater units are generally preferred over an electrical heating system that could create electromagnetic interference with the instrumentation. [13] They lack moving parts that could break down and overall provide a "highly reliable, continuous, and predictable output of heat". [13]

The RHU's plutonium fuel pellet is contained within a platinum-rhodium clad, a graphite insulator, and then an outermost heat shield. These safety features protect it against accidental re-entry events in which the unit may experience atmospheric heating and a ground impact. [13] Since it is individually packaged in such a durable capsule, a RHU is extremely unlikely either to sustain major damage from external radiation or meteorites or to cause damage by releasing radioactive materials. And if one RHU does sustain damage, it will not affect the integrity of other units or compromise their plutonium fuel within.

2.4 Cassini Mission Specifications

The Cassini mission was chosen as a model due to the timing of its launch and the existence of sufficient resources on Cassini to prove helpful to this project. Having launched the Cassini spacecraft in 1997, NASA scientists have had fifteen years in which to collect and analyze data on the performance of the RTG power sources. Admittedly, in fifteen years the radioisotope power system technology has changed to be more efficient and the GPHS-RTG models are currently being phased out. The GPHS-RTG may not continue to be used in the future but its parts and technology will. For example, the ASRG (Advanced Stirling Radioisotope Generator), one of the two models about to replace the GPHS-RTG, contains two GPHS fuel modules, which hold a total of 0.8 kg ^{238}Pu fuel. [6] The ASRG is still at the testing phase and has not yet been inserted into the field. The other model, a Multi-Mission RTG (MMRTG), will power the Mars Science Laboratory rover, which is not scheduled to land on Mars until August 2012. Both models have very little performance data published and so are not useful in this study.

The Cassini spacecraft was designed for a mission lasting 10.7 years: 6.7 years to reach Saturn and another four to conduct its intended scientific mission. [2] The primary mission ended on June 30, 2008, but as of spring 2012, Cassini finished its original mission almost four years ago and is still functional and collecting data for supplementary missions. [22, 4]

The mission standards for Cassini state

> the electrical power system must satisfy a variety of performance and implementability criteria, including the following:
>
> - Operation during and after passage through intense radiation fields, such as those near the Earth and surrounding Jupiter
> - Provision of sufficient power at distances of between 0.63 and 9.3 AU from the Sun
> - Operation with a a low mass-to-power ratio
> - Provision of a long-term (12 years) source of electrical power with high reliability.

[2] In addition to the general criteria for radioisotope power systems listed in Section 1.2, the radioisotope fuel in Cassini's RTGs must fulfill all of these mission-specific criteria. This study addresses the second, third and fourth points. Solar arrays did not fulfill all of the criteria because the intensity of sunlight at Saturn is too low for even todays array technology to provide the power required. The original Cassini spacecraft travelled as close as 0.63 AU to and as far as 9.3 AU from the Sun, outside the range in which solar panels are viable sources of power. [2]

2.4.1 Mass Allowance

Cassini needs 3 RTGs to provide electrical power "for its engineering subsystems and science payload", each of which is 56 kilograms, for a total of 168 kg. [2] A GPHS-RTG normally contains 10.8 kg of plutonium dioxide fuel at launch, 7.6 kg of which is pure ^{238}Pu, but Cassini was launched with extra fuel, 7.7 kg of which was ^{238}Pu. [2, 11] Cassini also had 117 RHUs to regulate the temperatures of the spacecraft's instrumentation. [8] Each RHU has a 0.00267 kg fuel pellet and a total mass of 0.040 kg. [13, 27] In total, the mass of the plutonium dioxide fuel on Cassini is 32.7 kg and the mass of the pure ^{238}Pu is 23.4 kg. The initial total mass of the power and heating systems is 172.68 kg.

The replacement radioisotope should not emit particles or rays other than alpha, because alpha particles require the least shielding to protect nearby sensitive instruments. Any other type of radioactivity would require stronger shielding that takes up both extra mass and extra space on a space probe.

2.4.2 Power Standards

The RHUs should produce 1 thermal watt to "maintain specific components on a spacecraft within normal operating ranges." but the beginning- and end-of-mission outputs are not specified. [27]

Each GPHS-RTG is "designed to provide 285 watts of electrical power at the beginning of the mission (BOM) from 4300 watts of decay heat" and 28 volts. [27] Since Cassini's RTGs were launched with extra fuel, they each provided 294 watts electric at BOM. [11] At the end of the 10.7-year mission (EOM), each RTG should have produced at least 225 We and actually provided an average 231 We. [2, 22] As mentioned in Section 2.3.1, RTGs produce less power over time because some of the radioactive heat source has decayed away and because the SiGe thermocouples degrade. The output currently decreases by about 9 watts each year. However, that loss was higher at the start of the mission because the thermocouples degrade substantially in the first few years. [3]

The Power and Pyro Subsystem regulates the electricity produced by the RTGs to supply a constant 30 volts DC to all of Cassini's electronics. [24] The system relies on the ability of the RTGs to supply a perpetual stream of energy. It does not contain a battery to store the energy so the electricity is sent immediately to the instruments. [22]

A single RTG is designed to hold 10.8 kg plutonium dioxide, of which 70.810% or 7.64748 kg is pure ^{238}Pu. That amount of plutonium dioxide is designed to produce 4300 W thermal at launch, and ^{238}Pu accounts for 99% of this initial power output. Cassini's three RTGs were modified to each contain 7.7 kg of pure ^{238}Pu so each one should have had 10.8742 kg fuel and produced 4330 W. The power output from one RTG due solely to the decay of 7.7 kg of ^{238}Pu is 99% of that value, or 4286 W at launch. Using Equation 14 with $t = 0$ and $m0 = 7.7$ kg, the power is calculated to be 4283 W per RTG, a 0.040% difference from the estimated actual value of 4286 W. This small discrepancy is likely due to the model not accounting for the very unlikely decays to a daughter nucleus in a highly excited state and with slightly lower kinetic energy, which would decrease the decay's average energy. As the difference is very small, the calculated 4283 W value is set as the BOM power output for ^{238}Pu in the Cassini mission model and will be used for comparison to the other isotope power outputs. To check this value, the total BOM power output from all three RTGs was measured to be about 13000 W and is calculated to be 3×4283 or 12.848 kW.The power output at EOM, at the end of 10.7 years, again using Equation 14 is calculated to be 3936 W. Since the calculated BOM power was very close to the actual value, it follows that the calculated EOM power is close to the actual EOM value. The actual EOM thermal power value could not be found. All sources preferred to state the EOM electric power value but the electric power model has an extra time-dependent variable to account for the degradation of thermocouple efficiency over time so the electric power output decreases at a faster rate than the thermal power output. This model will therefore use 3935.62 W as the EOM power value for 7.7 kg of ^{238}Pu to compare against the other radioisotopes' modeled behaviors.

Isotope	Half-Life (years)	α-decays / All Decays
^{238}Pu	87.74	100%
^{209}Po	102	99.52%
^{232}U	70.6	~100%
^{243}Cm	29.1	99.71%
^{244}Cm	18.11	100%
^{249}Cf	351	100%
^{250}Cf	13.08	99.92%
^{251}Cf	898	~100%

Table 2: This table shows the half-lives of the isotopes included in this study and the fraction of their decays that are α-decays.

3 Methods

Starting with seven radioisotopes that release the same type of radiation and have similar decay rates to ^{238}Pu, this paper models each isotope's power output, half-life, and mass, comparing them to the power needs and safety standards of the Cassini space probe. Seven isotopes were selected for this study as possible alternatives to ^{238}Pu: ^{209}Po, ^{232}U, ^{243}Cm, ^{244}Cm, ^{249}Cf, ^{250}Cf, and ^{251}Cf all have at least a 95% alpha decay mode and half-lives between 5 and 1000 years [Table 2]. Alpha decay was chosen as the primary decay branch because its radiation can be shielded easily and with little added mass. It is the safest radiation source for both technicians who work around it before launch and instrumentation that will be placed nearby.

The ^{238}Pu in RPS fuel is in the form of a ceramic oxide as a safety precaution against its dispersal after severe destruction of the radioisotope casing from an accidental atmospheric re-entry. The event is highly unlikely but serious enough to warrant safeguards. Each of the seven isotopes in this study forms a ceramic oxide according to its most common oxidation state, with the exception of californium. Californium's most common oxidation state is +3 so it would most often form californium (III) oxide, Cf_2O_3. Yet "all attempts to reduce or oxidize californium (III) [have] failed." [1] It also has a less common oxidation state of +4 so it can form CfO_2 instead. The resultant ceramic oxides are shown in Table 3. As noted in the Section (Ceramic Oxides), the oxidation number is dependent on an atom's electron shells, not its neutron number. Thus, the curium and californium isotopes form the same respective oxides, albeit with slightly different molar masses.

3.1 Assumptions

Assume that the oxide form does not affect the isotopes decay rate or decay energy. Assume that the composition of RTG fuel for the Cassini mission is standard for RTG fuel used in all missions. Assume t = 0 is BOM or launch. Assume all the power comes from the one isotope. The assumption is made that none of the plutonium has decayed to uranium or americium, (freshly processed fuel). The RHU fuel composition is unknown so the RHU models assume the isotope oxide fuels are composed entirely of that isotope and oxygen because calculating the proper enrichment of the oxide fuel for each isotope is beyond the scope of this paper. For example, the modeled plutonium (IV) oxide is 86.2% ^{238}Pu and 13.8% oxygen, by mass.

Element	Most Common Oxidation State	Less Common Oxidation States	Ceramic Oxide Selected
Plutonium	4	3 5 6 7	PuO_2
Polonium	4	-2 2 6	PoO_2
Uranium	6	3 4 5	UO_3
Curium	3	4	Cm_2O_3
Californium	3	2 4	CfO_2

Table 3: This table shows the oxides formed from plutonium and from the isotopes in this study. Note the oxidation number is dependent on an atom's electron shells, not its neutron number so isotopes form the same oxides.

For RTGs, Cassinis plutonium (IV) oxide fuel was 70.8% ^{238}Pu, 11.9% oxygen, 14.9% other plutonium isotopes, and 2.41% other actinides or impurities, by mass. [2] Assume that the alternative isotope oxide fuels will be enriched to a similar composition to plutonium dioxide fuel. For the RTG models that depend on volume, 85% of the isotope oxide fuels are assumed to be composed entirely of that isotope and oxygen, and the other 15% is for purities that do not contribute to the power output.

Each oxide fuel in the model is assumed to be purely that particular isotope and oxygen Assume that when each isotope fuel is made into its final doped form, the main isotope composition is the same fraction for each fuel. The model assumes that all power comes from the main isotope in the fuel. The power output of the doping products may be greater or lesser than that of the pure isotope depending on their half-lives and decay energies, so this assumption can overestimate or underestimate the total power. However, if all the other isotope fuel compositions are similar to ^{238}Pu, the density of the other isotopes of that element will be the same because the oxide formation depends on electrons, not neutron numbers. There is only 2.41% in plutonium dioxide fuel that is not plutonium or oxygen. This small percentage of similar actinides should not change the density or mass drastically. Therefore the density of the mixed oxide fuel will be approximated as the actual density of plutonium (IV) oxide.

In RTG fuel, ^{238}Pu has at least two orders of magnitude greater activity at launch than any other isotope fuel component so it is responsible for at least 99% of the power production. In RHU fuel, ^{238}Pu accounts for 99.9% of the heat output. [27]

3.2 Power Calculations

First, to confirm that α-decay is an energetically favorable process for the seven isotopes in this study and to verify the amount of energy released in the process, the separation energy of the α-particle from the parent nucleus can be calculated using Equation 11. The separation energy must be negative in order for the process to be energetically favorable, and is the negative of the energy released. The energy that is released is transferred into the kinetic energy of the α-particle and the recoil of the daughter nucleus. The isotopes' calculated and accepted energies released, assuming the daughter nucleus is formed in the ground state, are shown in Table 4. The calculated energy released overestimates the kinetic energy of the α-particle because it does not account for the recoil of the daughter nucleus. The recoil energy is quite small compared to the α-particle's kinetic energy, hence the relatively small

Isotope	Calculated Energy Released (MeV)	Accepted Energy Released (MeV)	Percent Error
^{238}Pu	5.593	5.499	1.71%
^{209}Po	4.980	4.883	1.97%
^{232}U	5.414	5.320	1.76%
^{243}Cm	6.169	5.992	2.95%
^{244}Cm	5.902	5.805	1.67%
^{249}Cf	6.296	5.946	5.89%
^{250}Cf	6.128	6.030	1.63%
^{251}Cf	6.176	6.017	2.64%

Table 4: This table shows the calculated and accepted energy values released by α-decayof the isotopes if the daughter isotope is formed in the ground state.

percents error.

$$E_{separation} = c^2(-m(Z,N) + m_\alpha + m(Z-2, N-2)), \tag{11}$$

where $E_{separation}$ is the separation energy, c is the speed of light, $m(Z,N)$ is the mass of the parent nucleus with Z protons and N neutrons, m_α is the mass of the α-particle and $m(Z-2, N-2)$ is the mass of the daughter nucleus.

The average energy released during an isotope's decay, E_avg, is

$$E_{avg} = E_1 f_1 + E_2 f_2 + E_3 f_3, \tag{12}$$

where E_1, E_2, E_3 are the three most common decay energies of the parent and f_1, f_2, f_3 are the respective fractional probabilities of the decay modes. E_1 is the energy released for the daughter nucleus to form in the ground state and E_2 and E_3 the energies to form it in the first two excited states. They make up over 99% of the total possible energy for all seven isotopes.

The thermal power output, or energy per unit time, of a radioisotope at a given instant is equal to the average energy of a single decay times the activity (number of decays per unit time) at the same given instant:

$$P(t) = E_{avg} \frac{\lambda N_A m_0 e^{-\lambda t}}{M} \tag{13}$$

where $P(t)$ is the power output function, t is time, E_{avg} is the average decay energy, λ is the decay constant, m_0 is the initial fuel mass, and M is the molar mass. λ can be computed from the isotope's half-life and Equation 10.

There are three power models to answer this study's original three research questions. The models can be applied to pure isotope fuel or the isotope as a ceramic oxide.

3.2.1 Model 1. Power density of the alternative fuels

The power density, otherwise known as specific power, is the power per unit mass. The power density is given by dividing Equation 14 by m_0:

$$D(t) = E_{avg} \frac{\lambda N_A e^{-\lambda t}}{M}, \tag{14}$$

Cassini Mission Standards	
Mission Length	10.7 years
BOM Power	4283 W
EOM Power	3935 W
m_0 [Pure]	7.7 kg
m_0 [Oxide]	8.9 kg
V_0	7.8×10^{-4} m^3

Table 5: Specifications for power output at the beginning and end, initial masses (pure isotope and oxide) and initial volume of ^{238}Pu fuel for the Cassini mission.

where $D(t)$ is the power density function, t is time, E_{avg} is the average decay energy of the isotope, λ is the decay constant of the isotope in the fuel, and M is the molar mass of the pure or oxide isotope. The molar mass for the pure isotope is slightly smaller than the molar mass for its oxide form. The oxide M value should be the known compound's molar mass divided by the isotope's subscript. For example, M of Cm_2O_3 in this equation is half the known molar mass because there are two curium atoms per molecule.

3.2.2 Model 2. Replacing plutonium dioxide in Cassini's RTGs

At launch, each of Cassini's three RTGs contained 10.8 kg of mixed plutonium dioxide, of which 7.7 kg was ^{238}Pu and 8.9 kg was $^{238}PuO_2$. The ^{238}Pu fuel has a volume of 0.00078 m^3 and should have provided 4283 W at BOM and 3936 W at EOM. Of these four key values of the initial fuel mass, the initial fuel volume, and the initial and final thermal power outputs [summarized in Table 5], one can be held constant and the other three solved for, using the known density of plutonium dioxide, the mission length, and Equation 14. By replacing the plutonium-specific values with those of the five remaining isotopes in this study, one can calculate the mass, volume, and power outputs of the alternative isotopes and compare the effectiveness of such fuels to ^{238}Pu. One can compare the isotopes in their pure forms or as ceramic oxides.

From the four key values, three sub-models can be made to compare plutonium against the five potential isotopes. One sub-model holds constant initial mass, another volume, and the last EOM power. There is no need for a sub-model that holds the BOM thermal output constant because it would be biased against any isotope with a half-life shorter than ^{238}Pu as it would decay away too quickly to also fulfill Cassini's EOM power needs. Note that m_0 is always the amount of fuel that can decay; oxygen doesn't count.

If the initial fuel mass is set to 7.7 kg (pure) or 8.9 kg (oxide), the BOM and EOM power outputs can be calculated from this initial mass by setting t equal to 0 and 10.7 years, respectively in Equation 14. The initial volume of the fuel is then the initial mass divided by the fuel's density. This sub-model's purpose is to compare the isotopes' expected performances if fuel mass were the limiting factor for the mission.

If holding EOM thermal power output equal to 3936 W and t = 10.7 years, the minimum initial mass of fuel that would produce that power output can be calculated using Equation 14. Once the initial mass is known and t is set equal to 0, the initial power output from that amount offuel can be found. The initial volume of the fuel is then the initial mass divided by the fuel's density. Taking into consideration that scientific missions, including Cassini plus both Mars Exploration rovers and both Voyagers, are often extended far beyond

RHU Design Standards	
BOM Power	n/a
EOM Power	>1 W
m_0 [pure]	2.67×10^{-3} kg
m_0 [oxide]	2.29×10^{-3} kg
V_0 [pure]	1.95×10^{-7} m^3
V_0 [oxide	2.05×10^{-7} m^3

Table 6: Specifications for power output at the beginning and end, initial masses (pure isotope and oxide) and initial volumes (pure isotope and oxide) of ^{238}Pu fuel for RHUs.

their intended mission length and that the alternative fuels that initially perform best drop off in power output the quickest, this sub-model is unlikely to prove useful.

If holding initial fuel volume equal to 0.000780m^3 (either pure or oxide), the initial fuel mass is the density multiplied by the volume. For the oxide calculations, the mass of pure isotope is its molar fraction times the initial oxide fuel mass. That is, $m_{pure} = m_0 \times \frac{M_{pure}}{M_{oxide}}$. The BOM and EOM power outputs can be calculated from the isotope mass by setting t equal to 0 and 10.7 years, respectively in Equation 14.The purpose is to model the amount of fuel that could fit in the existing RTG modules and this sub-model is thereby useful to find the isotopes suitable to replace plutonium in Cassini *with little modification to existing components.*

3.2.3 Model 3. Replacing plutonium dioxide in RHUs

At launch, a RHU contains 2.67×10^{-3} of mixed plutonium dioxide (or 2.05×10^{-7} m^3) and 2.2945×10^{-3} kg of pure ^{238}Pu (or 1.95×10^{-7} m^3). The RHU should provide at least 1 W thermal over the course of the mission, i.e., the minimum EOM power output from ^{238}Pu is 1 W. [27] Assuming a mission length of 15 years,

$$P(t = t_{ML}) = E_{avg} \frac{\lambda N_A m_0 e^{-\lambda t_{ML}}}{M} = 1 \tag{15}$$

The lambda and M are unique to each isotope and N_A is constant; therefore the only unknown variable is m_0. Having solved for the m_0 that produces the desired EOM power output, the BOM power output from the same amount of fuel can be calculated using Equation 16,

$$P(t = 0) = E_{avg} \frac{\lambda N_A m_0}{M}. \tag{16}$$

Of these three key values of the initial fuel mass, the initial fuel volume, and final thermal power outputs [summarized in Table 6], one can be held constant and the other two plus the initial power output solved for, using the known density of plutonium dioxide, the mission length, and Equation 14. By replacing the plutonium-specific values with those of the five remaining isotopes in this study, one can calculate the mass, volume, and power outputs of the alternative isotopes and compare the effectiveness of such fuels to ^{238}Pu. One can compare the isotopes in their pure forms or as ceramic oxides.

From the three key values, three sub-models can be made to compare plutonium against the five potential isotopes. One sub-model holds constant initial mass, another volume, and the last EOM power.

If the initial fuel mass is set to 2.67×10^{-3} kg (pure) or 2.29×10^{-3} kg (oxide), the BOM and EOM power outputs can be calculated from this initial mass by setting t equal to 0 and 15 years, respectively, in Equation 14. The initial volume of the fuel is then the initial mass divided by the fuel's density. This sub-model's purpose is to compare the isotopes' expected performances if fuel mass were the limiting factor for the mission.

If holding EOM thermal power output equal to 0.999 W and t = 15 years, the minimum initial mass of fuel that would produce that power output can be calculated using Equation 14. Once the initial mass is known and t is set equal to 0, the initial power output from that amount offuel can be found. The initial volume of the fuel is then the initial mass divided by the fuel's density. Taking into consideration that scientific missions are often extended far beyond their intended mission length and that the alternative fuels that initially perform best drop off in power output the quickest, this sub-model is unlikely to prove useful.

If holding initial fuel volume equal to 1.95×10^{-7} m^3 (pure) or 2.05×10^{-7} m^3 (oxide), the initial fuel mass is the fuel type density multiplied by the volume. For the oxide calculations, the mass of pure isotope is its molar fraction times the initial oxide fuel mass. The BOM and EOM power outputs can be calculated from the isotope mass by setting t equal to 0 and 15 years, respectively in Equation 14.The purpose is to model the amount of fuel that could fit in the existing RHU capsules and is thereby useful to find the isotopes suitable to replace plutonium in RHUs *with little modification to existing components*.

3.3 Sources & Availability

^{238}Pu and the seven isotopes in this study are not found in nature.

4 Results & Analysis

Each model was run twice, once with pure isotope values and again with isotope oxide figures.

4.1 Model 1. Power density of the alternative fuels

Pure ^{238}Pu has a known power density of 567.57 W/kg and was calculated to be 556 W/kg, a percent error of 2%. [27] If the plutonium model was so accurate, it follows that the other isotopes' calculated power densities are accurate as well. The results from the power density model are shown in Figure 3 for the pure oxides and in Figure 4 for isotope oxides over twenty years. The two plots follow the same trends but have slightly different y-intercepts because the isotope oxide values are a constant, large fraction of the pure isotopes. For example, the number of watts from one kilogram of the oxide $^{250}CfO_2$ is about 89% of the power output from one kilogram of its pure isotope, ^{250}Cf, since ^{250}Cf composes by mass 89% of 1 kg of $^{250}CfO_2$ and oxygen does not add to the power output.

Table 7 quantifies the results from the isotope oxide model. From smallest to largest power densities, ^{232}U, ^{243}Cm, ^{244}Cm, and ^{250}Cf in both pure and oxide forms have higher power densities than ^{238}Pu for over forty years. They have shorter half-lives than the plutonium so they are more energy dense at first but decay away at a faster rate. The most power dense isotope oxide, ^{250}Cf, has an initial power density of 3440 W/kg, over seven times the initial power density of ^{238}Pu oxide. Considering NASA missions are often around 3-10

Isotope Oxide	Power Density, t= 0 (W/kg)	Power Density, t= 15 yr (W/kg)	Power Density Value Compared to ^{238}Pu
$^{238}PuO_2$	479.6	426.0	n/a
$^{209}PoO_2$	418.8	378.2	Lower until t= 123 years
$^{232}UO_3$	554.8	478.8	Higher until t= 75.8 years
$^{243}Cm_2O_3$	1404	982.1	Higher until t= 67.5 years
$^{244}Cm_2O_3$	2502	1409	Higher until t= 54.4 years
$^{249}CfO_2$	111.9	108.7	Lower until t= 246 years
$^{250}CfO_2$	3445	1556	Higher until t= 43.8 years
$^{251}CfO_2$	36.51	36.10	Lower until t= 362 years

Table 7: The power density of each isotope oxide before it has decayed at all (t= 0) and after 15 years of decaying. The elapsed time before its performance matches that of ^{238}Pu and whether its power density is higher or lower than ^{238}Pu's before that point

years, and even allowing for delays in launch, all four isotopes would outperform plutonium at both the beginning and end of the mission, and are viable candidates to replace plutonium in future RPS that are built from scratch.

The power density of ^{209}Po is lower than that of plutonium, but close enough that it warrants further investigation. ^{248}Cf and ^{251}Cf have such long half-lives and therefore such low power densities that they would not really be favorable until 200 years after the start of the mission, which is an unrealistic mission length. ^{249}Cf and ^{251}Cf are removed from further consideration in the second and third models as an alternative fuel to ^{238}Pu.

4.2 Model 2. Replacing plutonium dioxide in Cassini's RTGs

The results from the power output model in which V_0 was held constant at 7.8×10^{-4} m^3 are shown in Figure 5 for isotope oxides over twenty years. The complimentary pure isotope plot [Figure 9] is almost identical and is located in the Appendix. Table 8 quantifies the results from the isotope oxide model. ^{244}Cm narrowly outperforms ^{250}Cf. The two radioisotopes exceed the power requirements by a large enough margin that they could fill one RTG and provide more power than three with plutonium dioxide fuel. In that case, the other two RTGs are superfluous and can be removed for a mass savings of 107-108 kg. ^{243}Cm is similar in that it can fill two RTGs and provide more than enough power for the Cassini mission over its lifetime, which would save 53 kg. Three RTGs filled with ^{232}U oxide would still slightly outperform plutonium dioxide because the former is less dense. Five RTGs filled with ^{209}Po would be required to fulfill the mission's power requirements. The extra generators would add 98.3 kg to the payload if it were used instead of ^{238}Pu.

If the amount of radioisotope is restricted to the allowable fuel volume of a RTG, ^{244}Cm, ^{250}Cf, ^{243}Cm, and ^{232}U all fulfill the mission requirements, act similarly to plutonium, and are viable candidates to replace plutonium in existing RTGs. For these instances in which the number of RTGs can be minimized, ^{209}Po is a poor alternative to that of plutonium. It is a relatively lightweight radioisotope, however, so it warrants further investigation in other types of models that want to reduce the fuel mass. If Cassini originally had only one generator, the more power dense isotopes would lose their advantage because the mission would still require at least one generator if replaced with the alternative fuel.

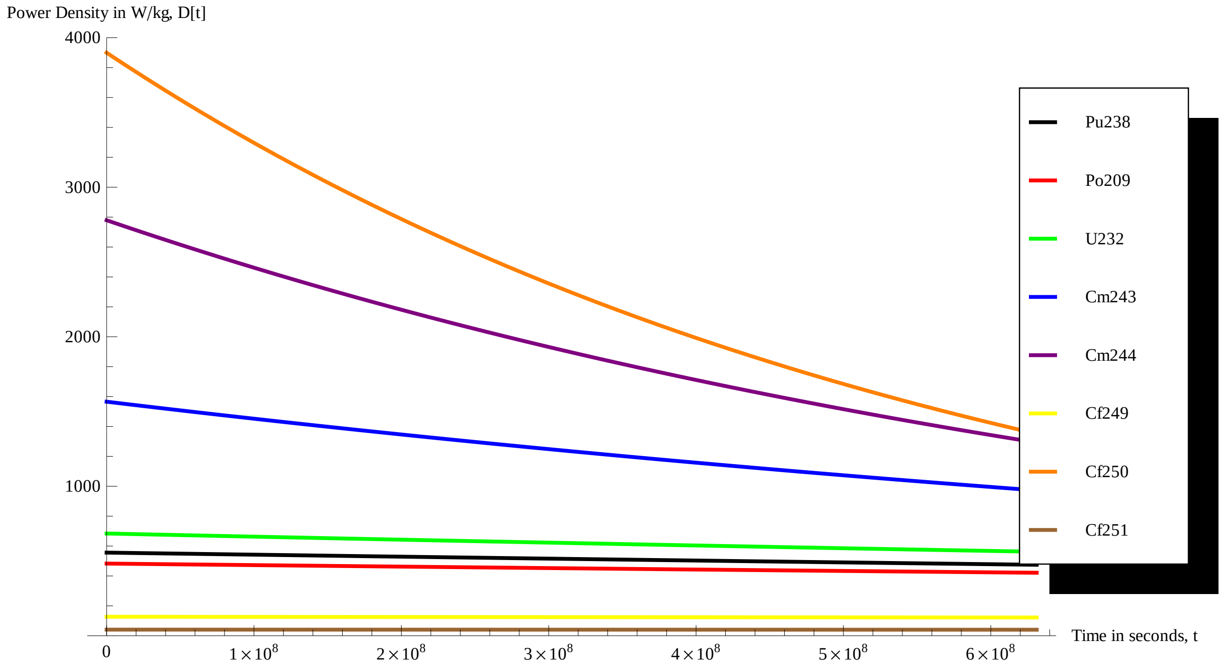

Figure 3: Power density of the seven pure isotopes in this study plus ^{238}Pu, in watts per kilogram, as a function of time.

4.3 Model 3. Replacing plutonium dioxide in RHUs

The results from the power output model in which V_0 was held constant at 2.0×10^{-7} m^3 are shown in Figure 6 for isotope oxides over twenty years. The complimentary pure isotope plot [Figure 12] is almost identical and is located in the Appendix. Table 9 quantifies the results from the isotope oxide model. A RHU filled with ^{209}Po or ^{232}U oxides would be less massive than one with ^{238}Pu because they are lighter isotopes. However, the ^{209}Po one does not nearly fulfill the power requirement of 1 W while the ^{232}U oxide does. The power dense ^{244}Cm, ^{250}Cf, and ^{243}Cm produce much more heat than is necessary and their fuel pellets are slightly more massive than ^{238}Pu's. Considering the amount of fuel in each RHU is so small and the mass differences between the alternative fuels and ^{238}Pu are about 1 gram, the possible mass savings or expenses are negligible.

If the amount of radioisotope is restricted to the allowable fuel volume of a RHU, ^{232}U fulfills the mission requirements, acts similarly to plutonium, and is a viable candidates to replace plutonium in existing RHUs. For these instances in which the number of RHUs cannot be minimized, ^{244}Cm, ^{250}Cf, are ^{243}Cm are a slightly worse alternative to that of plutonium. RHUs are different from RTGs in that one must minimize the number of RTGs to minimize mass but one cannot minimize the number of RHUs, only the mass of each RHU as the heat from the RHUs can only extend so far to the instruments around them. If the number of RHUs is minimized instead, one risks damage from the extreme cold of space to the instrumentation. To have the lightest RHUs possible, the best choice of fuel would be the one that provides at least the minimum heat output for the least amount of mass. If the volume of this fuel did not exceed the dimensions of the RHU fuel pellet, the difference

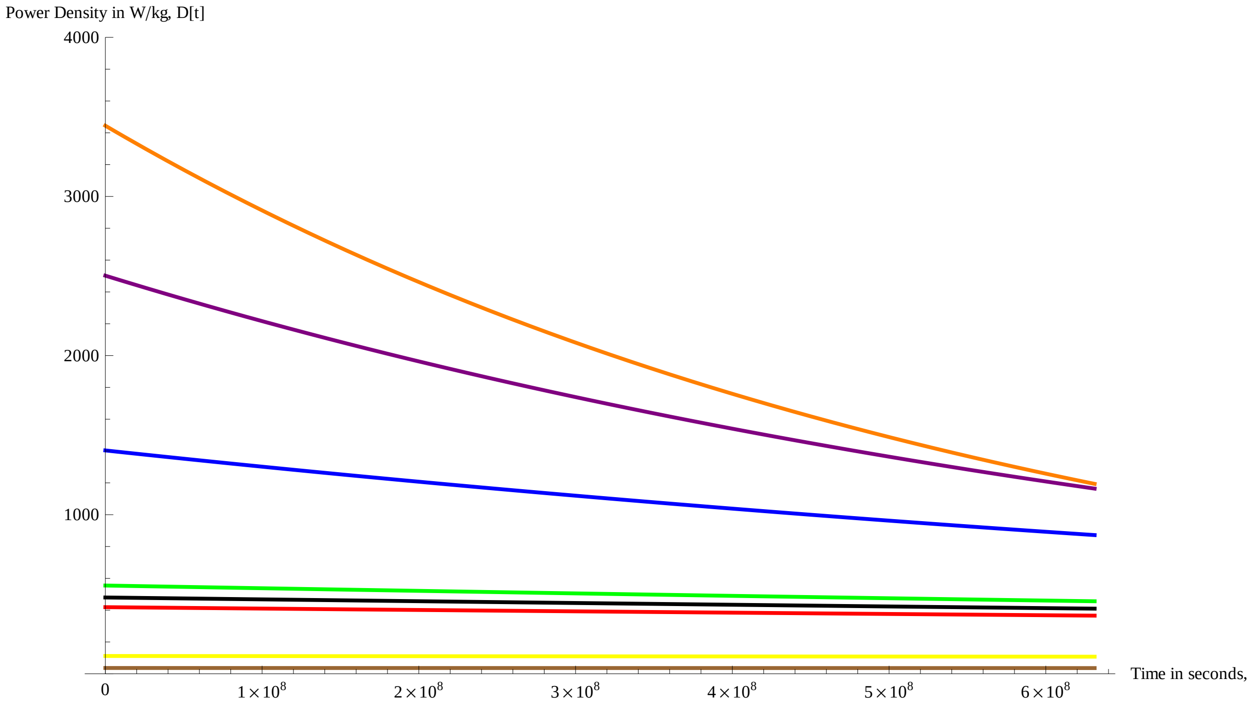

Figure 4: Power density of the seven isotope oxides in this study plus ^{238}Pu, in watts per kilogram, as a function of time. See Figure 1 for legend.

could be provided by a much lighter element that does not need to decay, such as oxygen, provided its presence did not sufficiently reduce the spread of the heat.

5 Conclusions & Recommendations

5.1 Conclusion

Ultimately the initial fuel volume and power density analyses were deemed the most important because the volume model is designed to fit the new fuel to the existing power components and the power density because it should be taken into consideration when new power components are being designed. In general, the cost of modifying existing hardware to be suitable for different fuel is prohibitive. But if the money will be spent anyway on creating new hardware, the new hardware should be designed for the more efficient fuels. Of the seven radioisotope fuels in this study, ^{243}Cm, ^{244}Cm, ^{250}Cf and ^{232}U have higher initial power densities than ^{238}Pu. ^{249}Cf and ^{251}Cf had too long half-lives and were quickly excluded from further analysis. ^{209}Po also has too low of a power output to be a viable candidate for replacing plutonium dioxide fuel. ^{232}U acts the most similarly to ^{238}Pu: it has a similar power output, molar mass, and density. ^{243}Cm, ^{244}Cm, ^{250}Cf generally far outperform ^{238}Pu. By expanding the radioisotope selection criterion to include half-lives less than 15 years, ^{250}Cf could be included in this study. Overall it performed the best and is recommended for further investigation. It has a half-life of 13.08 years and generates more power than an equal mass of ^{238}Pu (both in oxide form) for 43.8 years.

NASA has depleted its stores of ^{238}Pu, which is used primarily as a power and heat source on space probes. Due to the lack of fuel, future probe missions have been delayed,

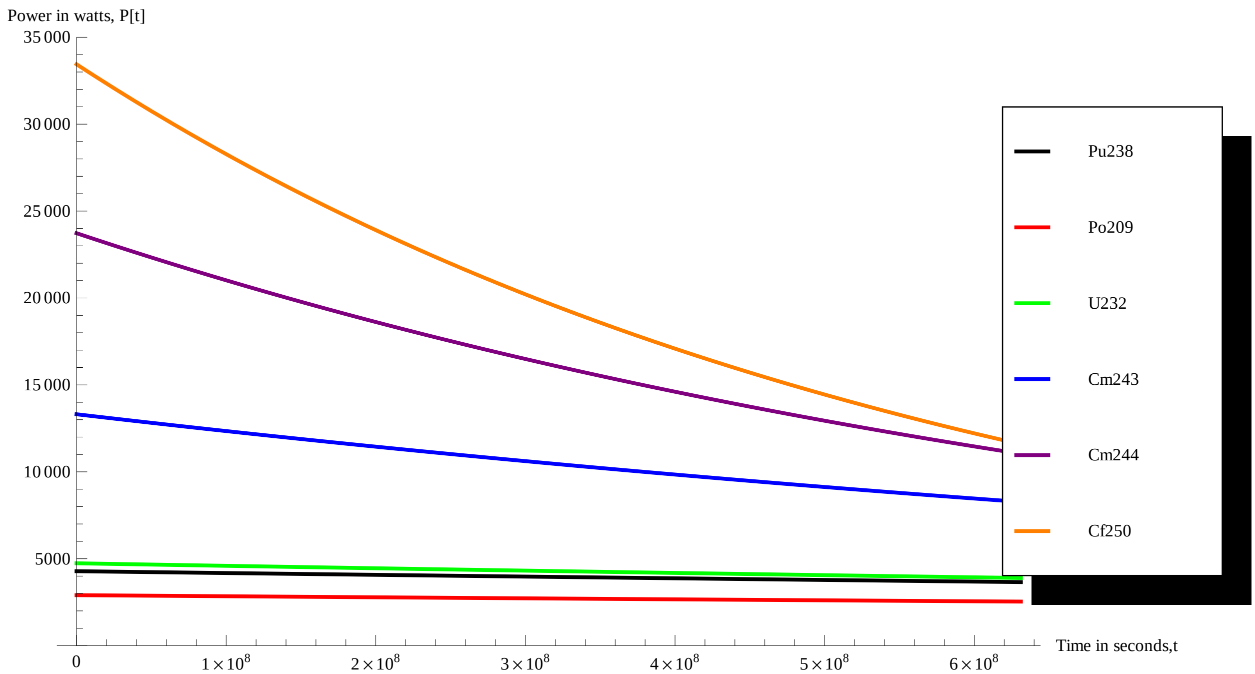

Figure 5: Power output of the five oxide isotopes in this study, in watts per kilogram, versus time, in seconds- if each has $V_0 = 7.8 \times 10^{-4} m^3$.

Isotope Oxide	BOM Power Output (W)	EOM Power Output (W)	Pure Isotope Mass (kg)	# RTGs Required	Mass Savings over ^{238}Pu (kg)
$^{238}PuO_2$	4283	3936	7.70	3	N/A
$^{209}PoO_2$	2904	2701	6.01	5	-98.3
$^{232}UO_3$	4738	4265	6.93	3	1.17
$^{243}Cm_2O_3$	13310	10320	8.50	2	53.0
$^{244}Cm_2O_3$	23730	15750	8.54	1	108
$^{250}CfO_2$	33440	18970	8.58	1	107

Table 8: The power output of each isotope oxide before it has decayed at all (t= 0) and after 10.7 years of decaying if V_0 of the oxide fuel is 7.8×10^{-4} m^3. The number of RTGs required to fulfill both the BOM and EOM power requirements and the mass savings or loss associated with using the alternative fuel and that number of RTGs.

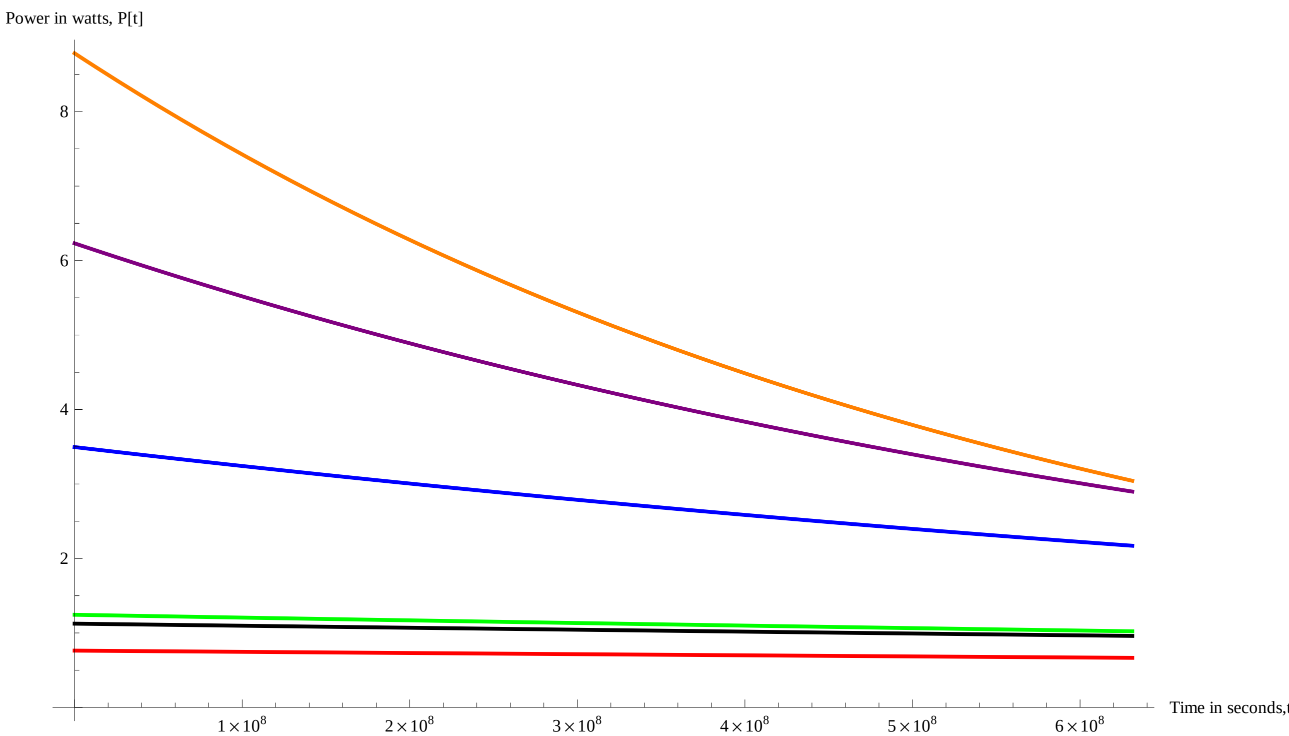

Figure 6: Power output of the five oxide isotopes in this study, in watts per kilogram, versus time, in seconds- if each has $V_0 = 7.8 \times 10^{-4} m^3$.

Isotope Oxide	BOM Power Output (W)	EOM Power Output (W)	Pure Isotope Mass (kg)	Mass Savings over ^{238}Pu (kg)
$^{238}PuO_2$	1.12	.999	0.00202	N/A
$^{209}PoO_2$	0.763	.689	0.00158	0.000524
$^{232}UO_3$	1.24	1.07	0.00182	0.000102
$^{243}Cm_2O_3$	3.50	2.45	0.00223	-0.000145
$^{244}Cm_2O_3$	6.23	3.50	0.00224	-0.000145
$^{250}CfO_2$	8.78	3.97	0.002225	-0.000205

Table 9: The power output of each isotope oxide before it has decayed at all (t= 0) and after 10.7 years of decaying if V_0 of the oxide fuel is 7.8×10^{-4} m^3. The number of RTGs required to fulfill both the BOM and EOM power requirements and the mass savings or loss associated with using the alternative fuel and that number of RTGs.

downsized or cut altogether. Since the DOE and its predecessors have been supplying NASA with ^{238}Pu for decades, the necessary technology and most of the facilities already exist to produce it. The problem is simply the lack of funds. Although four of the isotopes in this study show great potential for replacing ^{238}Pu, the much easier, cheaper, and faster option would be to restart ^{238}Pu production.

5.2 Recommendations

Future work to verify one of the alternative radioisotopes can replace plutonium dioxide includes investigating the phases of the metal isotopes to ensure they do not undergo a phase change within the operating temperatures of the fuel or change their crystal-structures. For example, metal U-235 must remain below 662C, at which point it changes from -phase to -phase and expands significantly. [28] The availability, sources, and proper enrichment of the fuel oxides must be reseached further. The heat source containment system was designed to consider the generation of helium from alpha decay from ^{238}Pu. However, it must be tested to check for compatibility with Cf-250 which has a shorter half-life and therefore produces helium at a faster rate than ^{238}Pu does. [27]

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