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High efficiency Dual-Cycle Conversion System using Kr-85

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HIGHLIGHTS

- Nuclear battery powered by a safe isotope: ^{85}Kr.
- Dual Cycle Conversion System achieving high energy conversion efficiency.
- Use of the Photon Intermediate Direct Energy Conversion system as top cycle.
- Use of a Stirling engine as the bottom cycle.
- Capable of high system efficiency (45% to 48%).

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ABSTRACT

This paper discusses the use of one of the safest isotopes known isotopes, Kr-85, as a candidate fuel source for deep space missions. This isotope comes from 0.286% of fission events. There is a vast quantity of Kr-85 stored in spent fuel and it is continually being produced by nuclear reactors. In using Kr-85 with a novel Dual Cycle Conversion System (DCCS) it is feasible to boost the system efficiency from 26% to 45% over a single cycle device while only increasing the system mass by less than 1%. The Kr-85 isotope is the ideal fuel for a Photon Intermediate Direct Energy Conversion (PIDEC) system. PIDEC is an excellent choice for the top cycle in a DCCS. In the top cycle, ionization and excitation of the Kr-85:Cl gas mixture (99% Kr and 1% Cl) from beta particles creates KrCl* excimer photons which are efficiently absorbed by diamond photovoltaic cells on the walls of the pressure vessels. The benefit of using the DCCS is that Kr-85 is capable of operating at high temperatures in the primary cycle and the residual heat can then be converted into electrical power in the bottom cycle which uses a Stirling Engine. The design of the DCCS begins with a spherical pressure vessel of radius 13.7 cm with 3.7 cm thick walls and is filled with a Kr-85:Cl gas mixture. The inner wall has diamond photovoltaic cells attached to it and there is a sapphire window between the diamond photovoltaic cells and the Kr-85:Cl gas mixture which shields the photovoltaic cells from beta particles. The DCCS without a gamma ray shield has specific power of 6.49 W/kg. A removable 6 cm thick tungsten shield is used to safely limit the radiation exposure levels of personnel. A shadow shield remains in the payload to protect the radiation sensitive components in the flight package. The estimated specific power of the unoptimized system design in this paper is about 2.33 W/kg. The specific power of an optimized system should be higher. The Kr-85 isotope is relatively safe because it will disperse quickly in case of an accident and if it enters the lungs there is no significant biological half-life.

1. Introduction

NASA's Radioisotope Thermoelectric Generator (RTG) technology used for deep space exploration is dependent upon a limited inventory of Pu-238 held by the National Laboratories of the United States (~ 39 kg as estimated in 2009 (Department_of_Energy 2005, 2013; National_Research_Council_Radioisotope_Power_Systems_Committee, 2009)). This inventory will suffice for several more missions. There has been discussion of increasing the Pu-238 inventory by using the separated Np-237 (~ 300 kg) in the United States inventory to produce an additional 5 kg of Pu-238 a year (Department_of_Energy, 2005). This option is expensive in that it requires a $100 million dollar commitment for infrastructure in addition to the $8 million dollars per kg price tag for the Pu-238. Another possibility is if the United States changes its policy on spent nuclear fuel reprocessing (a very controversial nonproliferation topic) and one that would require enormous investments. This change in policy would lead to a more than adequate source of Pu-238 for future space missions. There are cheaper options

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being examined. For example it is feasible to choose other isotopes such as Am-241 (Torre-Aguila et al., 2017). However, United States has a separated inventory of only 48 kg (Grimm, 2012; Torre-Aguila et al., 2017) and could only add a limited number of missions.

There are not many options for providing power for deep space missions in the long term. The development of small nuclear reactors is certainly part of the ongoing discussions. One approached uses an indirect method involving a two-step-process which begins by converting a radioisotope energy into optical energy and later converting the optical energy into electrical energy using a photovoltaic cell. The radioluminescence nuclear battery which uses a luminescent material such as phosphor as a photon conversion layer is based on this process (Russo et al., 2017; Xu et al., 2017; Yang et al., 2002; Zhang et al., 2017). The energy conversion efficiency of the radioluminescence nuclear battery depends on factors such as the type of radioisotope, its energy and emission angle, the matching between the photon emission energy and the band gap of the material, and self-absorption that occurs in the phosphor radioluminescence material. The draw back with the radioluminescence nuclear battery is that the reported efficiency is less than 1%.

This paper examines the possibility of improving the efficiency of an indirect conversion battery by using the Kr-85 radioisotope in a Dual Cycle Conversion System (DCCS), in order to maximize the efficiency of converting the power produced by the radioisotope into electrical power (Prelas et al., 1982, 1988).

2. The Dual-Cycle Conversion System using Kr-85 battery

Fission reactions produce Kr-85 as a byproduct at rate of 0.286% per fission and Kr-82 as a byproduct at a rate of 0.000285% (IAEA, 2017). Kr-82 is stable, so initially there are 1003 times more Kr-85 atoms than Kr-82 atoms that are produced by fission. Thus, if the Kr atoms produced in fission are extracted soon after being produced, the Kr-82 atomic density is assumed to be insignificant. Being gaseous, Kr-85 readily transports out of solid fuels and collects in gas pockets near the fuel cladding. If there was a desire to extract the Kr-85 from the fuel pin, it would be possible to accumulate sufficient inventories of Kr-85 to be of interest. The equilibrium inventory of Kr-85 stored in the spent fuel of the world's nuclear reactor fleet (assuming minimal losses) is approximately 2119 MCi and it is continually being produced at a rate of 147 MCi per year.

RTGs use a highly robust but relatively inefficient (~ 6–7%) energy transducer (Seebeck effect) for energy conversion. A simple means of extending the lifetime of the isotope stockpile is to increase the energy conversion efficiency of the transducer. There has been work done on improving the efficiency of a single cycle system such as certifying Brayton cycles and Stirling engines for space missions. Increasing energy conversion efficiency will extend the lifetime of the isotope stockpiles. A multicycle approach can also extend the lifetime of isotope stockpiles by increasing efficiency as well as being a conduit for adding new isotopes to the discussions. The key to implementing a multicycle approach is to use a topping cycle which has an operating temperature sufficiently high to provide the input temperature for lower stage energy convertors (see Fig. 1).

Through a combination of a top cycle capable of operating at a reasonably high temperature (between 800 and 1050 K) and a bottom cycle which has a reasonably high energy conversion efficiency in this temperature range, it is possible to maximize the efficiency of a DCCS for converting the power being generated from a radioisotope into electrical power. The DCCS using the Kr-85 isotope, does possess the capability of having a primary cycle with a high operating temperature and a bottom cycle which can efficiently convert the residual thermal energy into electrical power. In this scenario, the Photon Intermediate Direct Energy Conversion (PIDEC) system is used as the top cycle along with a bottom cycle such as the Brayton cycle or the Stirling engine.

The Kr-85 based DCCS essentially requires that the radioisotope be

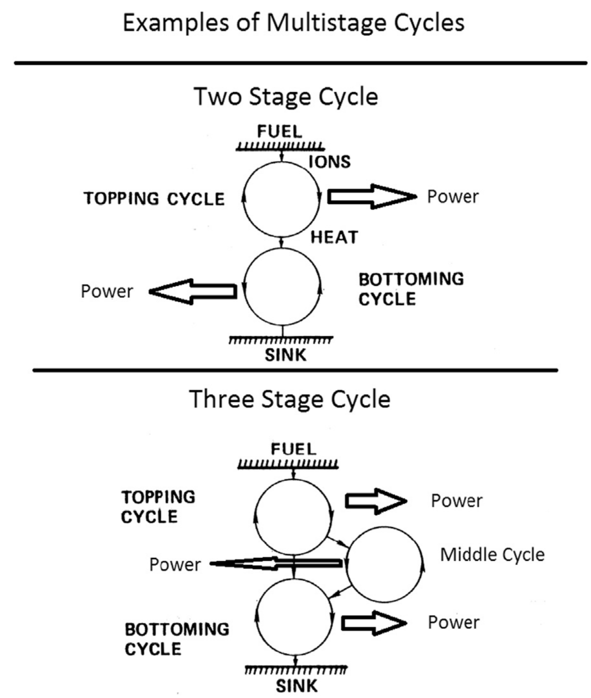

Fig. 1. An illustration of a two-stage and three-stage cycle approach (Prelas et al., 1982). In the two-stage approach, the ions from the fuel (e.g., radioisotope) provides the energy for the top cycle. The operating temperature of the top cycle is sufficiently high to be used as the high temperature input of a bottom cycle. In the three-stage cycle, the operating temperature of the second stage cycle would have to be sufficient to provide the high temperature leg for the third cycle.

part of the primary transducer - a method described as a volume source in the literature (Prelas et al., 2016). The PIDEC cycle is an indirect energy conversion system, so there is a primary and a secondary transducer. The primary transducer is made up of a fluorescing gas (i.e., Kr-85 is the predominant gas in the fluorescer). The beta particles emitted from the Kr-85 deposit their energy into the gas mixture (i.e., 99% Kr-85 and 1% chlorine for the base case that is described in this paper). The Kr-85 serves a dual purpose; it is both the source of ionizing radiation (e.g., beta particles) as well as being part of the primary fluorescence producing transducer (Fig. 2). The ionization and excitation created by the interaction of the beta particles with the primary transducer is used to create KrCl* excimer fluorescence. The KrCl* excimer is chosen for the base case studied in this paper because of its high fluorescence efficiency and good spectral match with the secondary transducer (31%-i.e., conversion of ionization and excitation

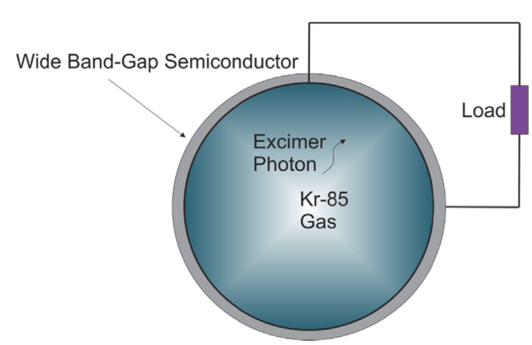

Fig. 2. Illustration of a Kr-85 powered PIDEC cycle. The Kr-85 gas is used as both the source of ionizing radiation and as a fluorescence source (e.g., the primary transducer). It produces excimer fluorescence which then interact with the diamond photovoltaic cells (the secondary transducer) surrounding the fluorescer (Prelas et al., 1993).