RADIOISOTOPE-DRIVEN DUAL-MODE PROPULSION SYSTEM FOR CUBESAT-SCALE PAYLOADS TO THE OUTER PLANETS. N. D. Jerred[1], T. M. Howe[1], S. D. Howe[1] and A. Rajguru[2], [1]Center for Space Nuclear Research (njerred@usra.edu) , [2]University of Southern California.

Introduction: It is apparent the cost of planetary exploration is rising as mission budgets declining. Currently small scientific beds geared to performing limited tasks are being developed and launched into low earth orbit (LEO) in the form of small-scale satellite units, i.e., CubeSats. These micro- and nano-satellites are gaining popularity among the university and science communities due to their relatively low cost and design flexibility. To date these small units have been limited to performing tasks in LEO utilizing solar-based power. If a reasonable propulsion system could be developed, these CubeSat platforms could perform exploration of various extra-terrestrial bodies within the solar system engaging a broader range of researchers. Additionally, being mindful of mass, smaller cheaper launch vehicles (~1,000 kgs to LEO) can be targeted. This, in effect, allows for beneficial exploration to be conducted within limited budgets.

Researchers at the Center for Space Nuclear Research (CSNR) are proposing a low mass, radioisotope-based, dual-mode propulsion system capable of extending the exploration realm of these CubeSats out of LEO.

Approach: The proposed radioisotope-based system would leverage the high specific energies [J/kg] associated with radioisotope materials and enhance their inherent low specific powers [W/g]. This is accomplished by accumulating thermal energy from nuclear decay within a central core over time. This allows for significant amounts of power to be transferred to a flowing gas over short periods of time. In the proposed configuration the stored energy can be utilized in two ways (see Figure 1): (1) with direct propellant injection to the core, the energy can be converted into thrust through the use of a converging-diverging nozzle and (2) by flowing a working fluid through the core and subsequent Brayton engine, energy within the core can be converted to electrical energy. The first scenario achieves moderate ranges of thrust, but at a higher Isp than traditional chemical-based systems. The second scenario allows for the production of electrical power, which is then available for electric-based propulsion. Additionally, once at location the production of electrical power can be dedicated to the payload's communication system for data transfer. Ultimately, the proposed dual-mode propulsion platform capitalizes on the benefits of two types of propulsion methods – the thrust of thermal propulsion ideal for quick orbital maneuvers and the specific impulse of electric propulsion ideal for efficient inter-planetary travel.

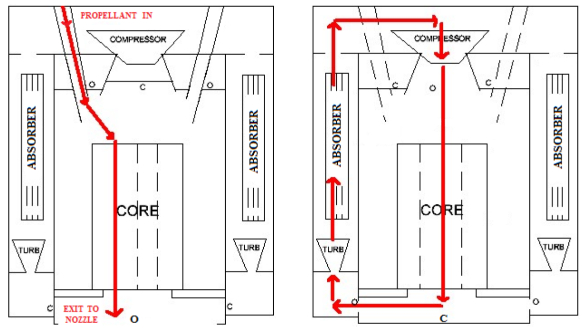

Figure 1: *diagram showing fluid flow for both the thermal (left) and electric (right) modes of the system*

Previous versions of this RTR-based concept have been studied for various applications [1-3]. The current version of this concept is being matured through a NASA Innovative Advanced Concepts (NIAC) Phase I grant, awarded for FY 2014. An artistic rendering of the current form of the concept for this study can be found in Figure 2.

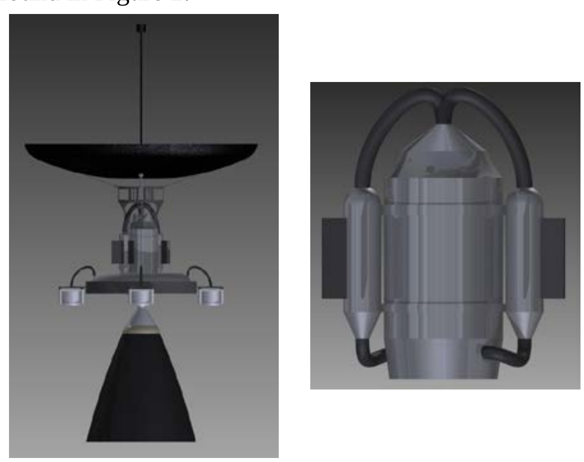

Figure 2: *conceptual artistic rendering of propulsion system (left) and main engine (right)*

In this study the RTR concept is being developed to deliver a 6U CubeSat payload to the orbit of the Saturnian moon - Enceladus. Additionally, this study will develop an entire mission architecture for Enceladus targeting a total allowable launch mass of 1,000 kg.

Concept: At the center of the propulsion system is the radioisotope fuel. In this study $^{238}PuO_2$ will be used to provide the decay energy. For safety and retention, the fuel will be encapsulated within a tungsten-based matrix [1,4]. The resulting fuel rods will be integrated within a central core material. The ideal core material must be capable of storing thermal energy, i.e., thermal capacitor, and then dissipating that energy to a flowing gas. Several materials have been identified elsewhere as being capable of achieving this task relying on their specific heat capacities, e.g., beryllium and boron tetra-carbide [1]. Instead, in this study the use of silicon as a thermal capacitor material is being considered. Silicon undergoes a latent heat of fusion ($\Delta H = 50.2$ kJ/mol) at 1685 K [5]. By taking advantage of silicon's latent heat of fusion, when gas is flowed through the silicon core a phase transformation from liquid to solid occurs. This in turn, will dissipate energy from the core to the gas at a constant core outlet temperature, yielding a constant chamber temperature or turbine inlet temperature depending on mode being used. For heat rejection, turbine exhaust gases will be passed through flow channels in a solid lithium block. Having a high heat capacity, the lithium block absorbs the thermal energy from the gas, which is then allowed to dissipate slowly between pulses. This method has the potential to deliver a low mass, compact heat rejection subsystem [2].

Mission Architecture: The trajectory analysis of a mission architecture serves as a crucial step to determine the feasibility of both the mission and the primary technology used for it. In this study the proposed propulsion system will propel itself from a geocentric orbit using phasing maneuvers, i.e., perigee pumping. This is accomplished by impulsing at the periapsis to induce apogee raising until transition in to the correct heliocentric orbit can be achieved for the interplanetary phase. Figure 3 shows a possible trajectory using perigee pumping. This technique of orbital escape aligns well with the RTR concept, where propellant is injected into the thermal capacitor and out of the nozzle and is then allowed to "recharge" through each orbit. In essence, the high thrust aspects of the thermal propulsion mode allows for a much quicker orbital escape then what is achieved through electric propulsion alone. Additionally, by employing a thermal propulsion mode, launch mass is minimized by negating the need for an upper stage motor. Once a heliocentric orbit is achieved the electrical mode will be employed powering either the communication or electric propulsion subsystems. Utilizing the high efficiency of electric propulsion through the interplanetary phase will aid in decreasing overall transit times.

An instrumentation package for an Enceladus mission with focused objectives can be assembled to fit with the limited constraints of a 6U package. Table 1 outlines possible instruments to be included. This study assumes the CubeSat payload has a dedicated radioisotope-based thermophotovoltaic (RTPV) battery with an output of 5 – 10 W [6].

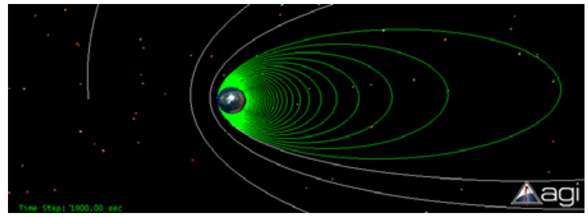

Figure 3: *orbital escape process utilizing the dual-mode system [3].*

In the exploration of the outer planets maintaining communication becomes about available power. On an Enceladus mission, a 10 W battery is not capable of handling the data transfer needed. However, utilizing the propulsion system's electric mode, the power needs at location can be maintained. Preliminary results indicate a 25 kg core can produce roughly 25 kW over a 6 min blowdown yielding manageable data transfer rates.

Table 1: *instrument package for mission architecture.*

	Mass [kg]	Volume [cm^3]	Power [W]
X-Ray/Gamma Ray Detector	*0.18*	*175*	*2.5*
Infrared Spectrometer	*0.23*	*180*	-
High Res. Camera	*0.166*	*501*	*0.66*
Mass Spectrometer	*0.25*	*32*	*0.5*

Conclusion: Preliminary numbers indicate a propulsion system can be designed to deliver a 6U CubeSat payload to Enceladus orbit with less than a 1,000 kg launch mass. Additionally, such a propulsion system allows for flexibility in both the payload size and mission destination with small changes in the launch mass. Ultimately, the proposed propulsion system not only extends the capabilities of CubeSat platforms but also extends involvement of outer planetary exploration to small research and university communities. This propulsion system provides the need of a low mass system for exploration to the outer planets where solar-electric and chemical-based propulsion systems are not feasible.

References:

[1] Jerred N. D. et al. (2012) *AIAA Space 2012*, Paper #5152. [2] Morgan S. et al. (2011) *NETS 2011*, Paper #3303. [3] Rosaire G. C. et al. *NETS 2013*, Paper #6736 [4] O'Brien R. C. et al. (2009) *J. Nucl. Mater., 393,* 108-113. [5] Gaskell D. R. (2003) *Intro. to the Thermodynamics of Materials, 4th Ed.*, 587. [6] Howe T. M. et al. (2012) *NETS 2012*, Paper #3059.