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Combustion-based power source for Venus surface missions

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ABSTRACT

The National Research Council has identified in situ exploration of Venus as an important mission for the coming decade of NASA's exploration of our solar system (Squyers, 2013 [1]). Heavy cloud cover makes the use of solar photovoltaics extremely problematic for power generation for Venus surface missions. In this paper, we propose a class of planetary exploration missions (for use on Venus and elsewhere) in solar-deprived situations where photovoltaics cannot be used, batteries do not provide sufficient specific energy and mission duration, and nuclear systems may be too costly or complex to justify or simply unavailable. Metal-fueled, combustion-based powerplants have been demonstrated for application in the terrestrial undersea environment. Modified or extended versions of the undersea-based systems may be appropriate for these sunless missions. We describe systems carrying lithium fuel and sulfur-hexafluoride oxidizer that have the potential for many days of operation in the sunless craters of the moon. On Venus a system level specific energy of 240 to 370 W_e-hr/kg should be possible if the oxidizer is brought from earth. By using either lithium or a magnesium-based alloy fuel, it may be possible to operate a similar system with CO_2 derived directly from the Venus atmosphere, thus providing an estimated system specific energy of 1100 W_{e+PV}-hr/kg (the subscript refers to both electrical and mechanical power), thereby providing mission durations that enable useful scientific investigation. The results of an analysis performed by the NASA Glenn COMPASS team describe a mission operating at 2.3 kW_{e+PV} for 5 days (120 h), with less than 260 kg power/energy system mass total. This lander would be of a size and cost suitable for a New Frontiers class of mission.

1. Introduction

Employment of solar powered planetary probes have been used/advocated extensively for planetary exploration (examples include Landis [2] and Landis et al. [3]). However, several targets of interest for solar system exploration require non-solar power sources due to permanent shading from craters or clouds, or due to extreme distance from the sun. These missions are often considered in the context of radioisotope power sources that employ the radioactive thermal decay and eventual electricity generation (RTG) of ^{238}Pu, as in the case of the Voyager missions to the outer solar system or the long-lived Apollo Lunar Surface Experiments Package. Robotic exploration on the surface of Venus has also been proposed using RTG-Stirling engine systems (Landis [2]), and RTG systems have been advocated for missions on Titan (Genta and Genta [4]), as well as Enceladus (Kostantinidas et al. [5]). The scarcity and expense of the required fuel reduces the number of missions that can be considered, let alone executed, in any decade. Though plutonium production has resumed in the United States at the writing of this paper, the cost and programmatic complexity of radioisotope power sources remains a barrier to its widespread use on space exploration missions (Mondt et al. [6]). Alternatively, Fribourg and Roux [7] advocate the use of nuclear systems based on pressurized water reactor technology rather than an RTG system. While some nuclear safety benefit appears possible, the system weight appear high, and it is unclear whether a cost benefit is realizable.

While battery power can be used for brief excursions into these sunless regions to advance our scientific understanding of these largely unexplored regions, probes must be able to operate for more than the time allowed by the specific energy available to chemical batteries. The Rosetta lander deployed with a system specific energy of at least 118 W_e-hr/kg (storing 900 W_e-hr in primary Li/$SOCl_2$ and 100 W_e-hr in secondary Li-ion batteries in less than 8.5 kg with an operating temperature range of −20 to 50 °C; see Debus et al. [8]). On Venus, with surface temperatures up to 452 °C, Na–S batteries have been advocated (Landis and Mellot [9]) with predicted system specific energy in the 300 W_e-hr/kg range (Landis and Harrison [10]).

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Advanced metal combustion systems for power generation that have significantly higher specific energy than primary batteries have been used for decades in underwater applications. An example of this is the Stored Chemical Energy Propulsion Systems (SCEPS) engines which have been built, tested, and fielded for driving torpedoes (Hughes et al. [11], Hsu [12]). In addition to mechanical/propulsive power, electric power can be produced via turbine-alternators and dynamic free-piston Stirling engines. These engines burn lithium in a closed system, providing high levels of power and energy in a challenging undersea environment. Not having to exhaust against a potentially large hydrostatic pressure means that operation of these engines is independent of depth. For planetary exploration, a closed system means that there are no exhaust products that might contaminate measurements taken of the surrounding environment.

By transitioning this mature form of power system technology from an extreme terrestrial environment to the extreme environments of space exploration, we can enable a new class of missions that will provide access to exciting science targets while addressing funding constraints, logistics and availability of radioisotope power sources. The more developed high specific energy metal-combustion power systems that carry both their own oxidizer and fuel could be potentially used in space applications where there is no atmosphere. Related, though less mature, technology has been tested where a metal fuel can react with carbon dioxide that is available from some planetary atmospheres. If successfully applied, combustion power systems could enable exploration of corners of the solar system that were previously the target of short-lived battery-powered probes or high-end nuclear-powered systems, resulting in a new era of low cost missions into the solar system.

This paper is comprised of three main sections. The first section serves as a SCEPS primer, in which the basic closed system Li/SF_6 chemistry and energy conversion philosophy is described as well as different possible energy conversion methods; a description of how this system is used underwater; and, by use of scaling arguments, how it might perform on the moon, Venus, and Mars. A mission to the surface of Venus is the eventual "target" of the present effort described here. In the second section, several basic closed system reaction fuel-oxidizer candidates will be described that attempt to address nominal requirements. A lithium fuel with a sulfur hexafluoride oxidizer energy system is one candidate. Others evaluated will benefit from taking advantage of the high reaction energy available between the carbon dioxide atmosphere and metal fuels including magnesium, magnesium/zinc alloy, magnesium/aluminum alloy, and lithium. By using the available atmosphere as an oxidizer, the system gains in mass-efficiency. The dense products of combustion can be stored in the system fuel tank, again eliminating the requirement of combustion product exhaust. In the third section, the results of a detailed trade study are presented using a reactant group chosen in the second section. This trade study was performed by the authors during five days with the NASA GRC COMPASS team, and had as one of its goals, the development of a conceptual design of a Venus lander that would be of suitable size and cost for a New Frontiers class mission.

2. Power and energy

2.1. Underwater with Li/SF_6

The first published work relating to the application of closed metal combustion power systems appears to be the patent of Pauliukonis [13]. Application to underwater power plants are first described by Biermann [14] and van der Sluys [15], and the topic was expanded upon by Groff and Faeth [16] and Hughes et al. [11]. In these works, the basic reaction involved with the stored chemical energy propulsion system (SCEPS) is:

$$8Li + SF_6 \rightarrow 6LiF + Li_2S + Heat \quad (1)$$

The standard heat of reaction at 298 K is 13 kW_{th}-hr/kg of Li (alternatively, 5.65 kW_{th}-hr/kg of SF_6 or 3.6 kW_{th}-hr/kg of the combined reactants). Note that the specific energies described here are for the reactants alone. By comparing these with other reactant couples later in the paper a comparison of the relative potential of candidate couples can be made. Eventually an assessment of the system specific energy will be made. The effect of the weight of such components as engines, reactant storage tanks, alternators and power conditioning electronics, and heat exchangers will be accommodated by the assessment.

This reaction has some particularly interesting features. At fuel bath/tank operational temperatures (~ 1100 to 1250 K) the lithium fuel and the products exist as liquids. As noted by Groff and Faeth [16,17], the products of the reaction are immiscible in the lithium fuel and are over three times denser. The practical result of this is that the products of reaction can be stored in the same volume that was once occupied by the fuel alone. Biermann [14] proposed that the heavier products initially formed spheres that were supported by the surface tension of the lithium surface until the spheres became large enough to fall through that surface. This behavior was verified by Groff and Faeth [16]. Also, because the products of combustion are a condensed phase, the reaction takes place at low pressures; typically near the vapor pressure of lithium (Herr et al. [18]).

Prior to the start of power production, the lithium is stored in a tank as a solid; and at the start of operation, the lithium is melted. For current terrestrial applications, the SF_6 oxidizer is stored in a separate tank as a saturated liquid with a vapor pressure of 22 bars (at 294 K). Sulfur hexafluoride at lower temperatures is inert, and as noted by Little [19], combustion on a quiescent molten lithium surface can only proceed above the melting point of the product (1065 K). In practical systems combustion can proceed in a moving lithium flow at or above the lithium melting point (453 K).

Hughes et al. [11] and Kiely [20] describe batch reactors that have been developed for application with this energy system; coupled to a steam Rankine power plant. Fig. 1 is a schematic of how a batch type reactor is used to drive a Rankine cycle power plant. Fig. 1a shows a schematic of a boiler/reactor in which the heat exchanger-boiler tubes make up an annular enclosure storing the fuel. The reaction energy is distributed throughout the fuel volume. The only place for the energy to go is into the enclosing tubes to boil and superheat the water with minimal losses from the insulated tank end covers. The steam produced is expanded through a turbine-gearbox to provide motive power or a turbine-alternator to provide electric power. The Rankine cycle condenser rejects heat to the ocean. Fig. 1b is a schematic of how the energy system is incorporated in a cylindrical undersea vehicle. In this configuration the energy convertor is surrounded by the heat rejection condenser. Other forms have been considered in which the boiler tubes are embedded in the bath volume. While water is currently used as a working fluid in terrestrial applications, other working fluids may be used as well. Because of the way heat is added to the working fluid in the batch combustor configuration, a closed cycle Brayton convertor might also be used as suggested by Harper and Jansen [21]. Faeth [22] presents the design and test results for a combustor developed for that purpose.

Fig. 2 is a sketch depicting the operation of a wick combustion system (from Kiely [20]). Fundamental research in this area was done by Groff and Faeth [16], and Blakeslee and Faeth [23]. Here molten lithium wicks up a porous structure from the fuel tank into the primary compact combustor by virtual of surface tension. The