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Coproduction of Volatiles and Metals from Extraterrestrial Materials

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Abstract

This report covers two main efforts in support of the general goals of SERC/culpr

1. We continue to investigate processes for the coproduction of metals from extra-terrestrial materials in conjunction with plausible schemes for oxygen extraction. Our principal emphasis has been upon the extraction and purification of iron from the ilmenite reduction process for oxygen, from the cathode metal deposits made in the magma electrolysis process for oxygen, and from native ferrous metal alloys on the Moon and asteroids. All work on the separation and purification of ferrous metals has been focussed upon the gaseous carbonyl process, a scheme that involves only temperatures attainable by passive thermal control.

2. We have begun to explore a variety of schemes, involving the use of several different propulsion options and both propulsive and aerobraking capture at Earth, for return of extraterrestrial resources to Earth orbits.

In addition, we continue to search out new opportunities in space resource utilization. Examples include continuation of work underway on the feasibility of locating Solar Power Satellites in highly eccentric Earth orbit, on the energetics of extracting the potential clean fusion fuel ^3He from the atmosphere for return to Earth, and on the utility of a nuclear steam rocket (using non-terrestrial water as the working fluid) for transportation in the inner solar system.

Introduction

In the broadest sense, an academic research center should be only loosely coupled to immediate practical concerns. Instead, it should seek vigorously to look at the broadest possible spectrum of opportunities. SERC's prime responsibility is to be the first to recognize potentially important new resources, to anticipate future human needs, to explore processing schemes and transportation techniques, and to identify the practical implications of the availability of non-terrestrial resources.

More specifically, one central effort of SERC activities is the extraction of volatiles from nonterrestrial materials for use principally as propellants. Because of the crucial role of oxygen as the dominant component of likely fuel/oxidizer combinations, extraction of oxygen from lunar and asteroidal materials has been given the highest priority. It seems clear, however, that any process that produces oxygen on the Moon will result in the coproduction of free ferrous metals in relatively large amounts. Any scheme that makes these metals into useful products with only a minor additional use of energy will greatly increase the total mass of useful product per unit of energy expended. The availability of a demonstrated, efficient scheme for coproducing oxygen and metals (and/or refractories) may be the deciding factor in the choice of the oxygen-manufacturing technology to be used on the Moon.

The two most extensively studied scheme for lunar oxygen production, the chemical reduction of ilmenite and magma electrolysis, are under intensive study at SERC. The two most pressing problems with ilmenite reduction are: 1) providing a reasonably clean ilmenite feedstock and 2) deciding which reducing agent to use and how to recyle it. The former is under study by Prof. Joachin Ruiz, who is working on electrostatic and magnetic beneficiation techniques for extraction of ilmenite from either the lunar regolith or crushed lunar basalts. The latter problem is under study by Prof. Farhang Shadman, who is exploring the kinetics of ilmenite reduction by gaseous hydrogen and carbon monoxide. The second scheme is being addressed Prof. Larry Haskin and Dr. Rudy Keller, who are studying electrochemical reduction of molten lunar simulants. The metallic byproducts of these two processes (metallic iron from ilmenite reduction and a complex metallic cathode deposit from magma electrolysis), as well as native ferrous metal alloys, are attractive starting materials for our extraction, separation, and fabrication schemes using gaseous carbonyl technology.

Progress in the Past Year

We have actively pursued the issues presented by the coproduction of metals with oxygen on the Moon. The technology we have chosen to emphasize is the gaseous carbonyl process for extraction, separation, purification and deposition of the ferrous metals. The fundamental patents for nickel carbonyl extraction are owned by INCO, and Formative Products Inc. holds most of the proprietary technology for fabrication of products by vapor deposition of nickel from nickel tetracarbonyl. We have surveyed the literature on the synthesis, purification, and handling of the transition metal carbonyls, and have designed and are building simple experimental setups for investigating carbonyl process applications to extraterrestrial settings. We have enlisted the participation of William Jenkin, the founder of Formative Products and developer of the commercial nickel-deposition technology, as a consultant on this project. He is working with us in a joint effort to develop new technologies to adapt the present carbonyl technology to space materials and conditions. Historically, carbonyl chemical vapor deposition (CVD) of nickel has been carried out commercially for many years. But iron, which is much more abundant (40-93%) than nickel (6-60%) in native non-terrestrial metals, has never been commercially fabricated into any product except analytic grade iron powder. The challenge has been to find a direct use for iron carbonyl CVD in fabricating "castings" or strong films.

We in our laboratory are concentrating on the volatilization behavior of native ferrous metal alloys with compositions relevant to the lunar regolith, metallic coproducts from lunar oxygen production schemes, and meteoritic metal alloys. Jenkin has been working on techniques for carbonyl CVD of iron. He has successfully demonstrated for the first time the deposition of pure, tough films of metallic iron by varying the carrier gas composition during iron carbonyl CVD.

We have also begun a program of calculation of opportunities for scientific and resource-retrieval spacecraft missions to near-Earth asteroids and the Mars system. We have so far screened the most recently discovered asteroids (for which no trajectory calculations have been reported previously) for their accessibility from low Earth orbit (LEO) and for the ease of return to Earth-intercept.

We have also examined the energetic and technological feasibility of returning the potential clean fusion fuel ^3He to Earth from the atmosphere of Uranus. The attraction of Uranus is that ^3He is present in a cold, dense gas mixture (hydrogen, helium, methane) with a concentration of 45 ppm. The alternative scheme for retrieval of nonterrestrial ^3He is based upon extracting solar-wind-implanted gas from the lunar regolith, where it has a concentration of only 0.01 ppm. We find that a single-stage-to-orbit nuclear rocket using liquid hydrogen as the working fluid can get the payload out of the Uranus atmosphere. The total energy cost per kilogram of ^3He returned to Earth is 1000 times smaller for ^3He from Uranus than from the Moon.

Finally, we have developed a scheme for fabrication of Solar Power Satellites from non-terrestrial materials in highly eccentric Earth orbit (HEEO). The advantages of HEEO are: a) HEEO is energetically more accessible than GEO (3.0 vs. 4.0 km/s above LEO) for conventional launch from Earth, and hence chemical boosters can deliver larger payloads to HEEO than to GEO, b) the total delta V for propulsive or aerobraking material return to HEEO is always much smaller than to GEO or LEO, regardless of whether the material originates from the Moon, the Mars system, or near-Earth asteroids, c) HEEO is nearly at Earth escape velocity, but allows propulsive escape burns to occur deep in Earth's gravity well, where they are most efficient, d) HEEO is much more accessible than GEO (or LEO) via electromagnetic launch from Earth's surface or the lunar surface, due to the very small post-launch delta V requirements for orbit-matching and rendezvous, e) return to Earth (or LEO) from HEEO is easier than from GEO, involving a much lower propulsive delta V and an equal or slightly higher reentry heating load. For similar reasons, HEEO is a highly desirable location for a refueling depot and propellant plant.

Related Publications

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