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Extraction of Volatiles and Metals from Extraterrestrial Materials

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J. S. Lewis

Lunar and Planetary Laboratory
University of Arizona

Abstract

Recent progress in defining the physical, orbital, and chemical properties of the Earth-crossing asteroid and comet population has been integrated into an elaborate Monte Carlo model of the fluxes of bodies in the inner Solar System. This model is of use in projecting flight opportunities to as-yet undiscovered near-Earth objects and in assessing the impact hazard to life on Earth and the evolutionary consequences of impacts on the other terrestrial planets. We also have made further progress in defining desirable transportation system architectures for the use of non-terrestrial volatiles and metals, including the delivery of propellants to near-Earth space for fuelling of SEI-type expeditions, the construction and resupply of Solar Power Satellite constellations in various Earth orbits (including GEO and Highly Eccentric Earth Orbit (HEEO)), and retrieval of ^{3}He for use as a clean fusion fuel on Earth. These studies suggest a greater future role for SERC in the exploration of space energy sources to meet Earth's 21st-century energy requirements. Laboratory studies of volatilization and deposition of ferrous metal alloys have demonstrated deposition of strong iron films from carbonyl chemical vapor deposition (CVD), showing the crucial role of additive gases in governing the CVD process, and pointing the way to specific experiments on extraction and deposition of ferrous metals from nonterrestrial materials.

General Research Program

This project includes research into three basic areas: prospects for accelerating the development of non-terrestrial sources of energy for Earth using non-terrestrial propellants and structural materials; transportation system studies on the most efficient return of non-terrestrial materials to near-Earth space for use in large-scale future space activities; and carbonyl processing of nonterrestrial ferrous native metals. In addition, this project includes oversight over SERC science program activities and travel for the purposes of developing research collaborations at other research centers and in industry. These activities are treated separately below.

Energy for Earth from Space

Over the past two years we have carried out preliminary studies of two different schemes for providing energy for Earth from space. These studies suggest that the energy needs of Earth in the 21st century can plausibly be met economically, and with diminished environmental impact, by either building Solar Power Satellites from asteroidal materials in Highly Eccentric Earth Orbit (HEEO) or by returning ^{3}He from the atmosphere of Uranus for use as a clean fusion fuel in reaction with terrestrial deuterium.

HEEO (in our reference example, 6000 to 400000 km altitude) has several considerable advantages relative to GEO as a site for construction of SPS constellations: 1) It is more accessible than GEO via chemical launch from Earth, the Moon, and near-Earth asteroids. 2) From HEEO there is much easier access to Earth than from GEO (a delta V of under 100 m/s vs. 1461 m/s for return to atmospheric entry), easier access to the Moon than from GEO (2900 vs. 3500 m/s), and easier access to the typical NEA than from GEO (3000 vs. 5400 m/s). 3) The radiation hazard in HEEO is no worse than in GEO, and the cost of providing shielding from any source will always be less in HEEO. 4) The high MPBRs available for return of asteroidal material suggested a careful look at a variety of boot-strapping schemes for return of large masses of asteroidal material to HEEO, using propellants derived from asteroids.

Alternatively, commercial production of electric power from fusion of ^{3}He with deuterium may be shown to be technically feasible. If so, then: 5) the preferred source for the ^{3}He is the atmosphere of Uranus, 6) ^{3}He return from Uranus requires two crucial items of new technology: a nuclear rocket stage using hydrogen as the working fluid and a "hot air balloon" filled with warm hydrogen to suspend the processing package in the uranian atmosphere. 7) Processing of the ambient atmosphere to separate helium from hydrogen and methane and to separate the isotopes of helium can be done using a small subset of the equipment required to extract ^{3}He from lunar regolith. Among the features of the lunar scheme that may be omitted entirely are a) the need to mine 10^8 tonnes of dirt per tonne of ^{3}He, b) the need to beneficiate and size minerals, c) the energy needed to heat 10^8 t of regolith to roughly 1000oC, d) the need for high process temperatures, e) the need to design around a two-week hot day and a two-week cold night, which creates severe temperature-cycling stresses and interrupts continuous processes, and f) the need to handle a wide range of reactive gases along with the ^{3}He.

Transportation System Architectures

Motivated in large part by the study of possible locations for SPS constellations summarized above, we have looked at a variety of bootstrapping schemes for return of nonterrestrial propellants and metals to near-Earth space. These studies, begun last year, originally involved space stations in highly eccentric Earth orbit as fuel-manufacture sites, near-Earth asteroids as sources of water, and both solar thermal and nuclear thermal "steam rockets" as the means of transport. Single-trip asteroid missions from HEEO were so promising that we were led to consider using the spacecraft for multiple round trips. Constraining the spacecraft specific impulse to 180 to 220 seconds (cool thrust chambers; very long operational lifetimes) and allowing a spacecraft operational life of 10 to 15 years (three round trips to a carbonaceous NEA by each spacecraft) we have demonstrated that real multiple-mission sequences to known near-Earth asteroids of probable C-type composition can provide mass payback ratios of about 100:1. Table 1 presents the model mass-payback ratio calculated for three round trips to a "typical good" NEA (a composite of the dozen best-known NEAs): case A3 in the Table assumes all delta V maneuvers above LEO, including capture into Earth orbit, are carried out using asteroid-derived water as the propellant. Case A4 uses, instead of propulsive capture, an asteroid-derived aerobrake. Table 2 shows that, for the same target asteroid, use of asteroidal propellant returned on the first mission to fuel an "armada" of retrieval vehicles can raise the mass payback to over 100:1. Table 3 documents a series of missions by a single spacecraft to the most accessible known C-type asteroid, 1977 VA. If the "armada" scheme is used from a base in HEEO, MPBRs over 50 can be achieved, as shown in Table 4. Finally, if the initial fueling of the "armada" is carried out in LEO, with all subsequent operations based in HEEO, the MPBR rises to over 80.

These logistic studies, in calling attention to several very attractive features of missions to retrieve materials from near-Earth asteroids, have served to motivate a more careful look at the mass budget, logistic systems design, and processing equipment requirements for realization of schemes

Table 1

Mass Payback Ratios
(three round trips; typical "good" asteroid)

Mission	Return to LEO	Return to GEO	Return to HEEO
E1	1.000	0.334	0.418
A3	3.7	7.8	16.6
A5	24.3***	15.9***	24.9**

* Assuming an aerobrake mass fraction of 0.2 (moderate energy dissipation)

** Assuming an aerobrake mass fraction of 0.3 (high energy dissipation)

Table 2

Mass Payback Ratios
(one trip for fuel; typical "good" asteroid; three-trip "Armada")
(all water returned on first trip used as fuel for new vehicles)

Mission	Return to LEO	Return to GEO	Return to HEEO
E1	1.000	0.334	0.418
A3	6.9	10.8	35.2
A5	92.0***	24.2***	115.0**

* Assuming an aerobrake mass fraction of 0.2 (moderate energy dissipation)

** Assuming an aerobrake mass fraction of 0.3 (high energy dissipation)

Table 3

Mass Payback Ratios
(four round trips for fuel to 1977 VA)

Earth Launch Date	dV outbound	dV inbound	Earth Arrival	MPBR
Nov 1990	5712	473	Nov 1995	7.0
Nov 1995	2367	316	Nov 2000	14.
Nov 2000	2322	1675	Nov 2005	21.
Nov 2005	2566	776	Nov 2005	28.

This model illustrates real multiple round trips to a single typical good asteroid, using trajectories from Lau and Hulkower (1985).

Original departure is from LEO, and all returns to Earth use an asteroid-derived aerobrake with a mass fraction of 0.2 (moderate E dissipation) to return to HEEO. Outbound propulsion for the first trip is H/O lifted from Earth; on subsequent trips it is H/O made by electrolysis of asteroidal water. Inbound propulsion is by solar thermal steam engine.

Table 4

Mass Payback Ratios
(one trip for fuel to 1977 VA; three-trip "Armada")
(all water returned on first trip used as fuel for new vehicles)

Earth Launch	Number of vehicles	dV out m/s	dV in m/s	Earth Arrival	Water Mass in HEEO (t)	MPBR
Nov 1990	1	5712	473	Nov 1995	100	7.0
Nov 1995	52	2367	316	Nov 2000	5200	17.6
Nov 2000	52	2322	1675	Nov 2005	10300	35.0
Nov 2005	51	2566	776	Nov 2010	15400	52.3

This model illustrates real multiple round trips to a single typical good asteroid, using trajectories from Lau and Hulkower (1985). All water returned by the first mission is used to fuel an "Armada" of vehicles delivered to HEEO from Earth. The lifetime of each vehicle is three missions (15 years).

Original departure is from LEO, and all returns to Earth use an asteroid-derived aerobrake with a mass fraction of 0.2 (moderate E dissipation) to return to HEEO. Outbound propulsion for the first trip is H/O lifted from Earth; on subsequent trips it is H/O made by electrolysis of asteroidal water. Inbound propulsion is by solar thermal steam engine.

to use propellants and metals derived from NEAs. In the 1992-1993 budget year we shall be applying the Figure-of-Merit (FoM) software developed at SERC by Ramohalli and his students to the assessment of the overall desirability of retrieval of asteroidal material. This will entail joint support of one engineering graduate student by Ramohalli and Lewis.

Gaseous Carbonyl Process

One of the most important results arising in this project over the past year and a half has been the result of a close and fruitful interaction with a consultant, William C. Jenkin, who is the leading developer of carbonyl chemical vapor deposition (CVD) technology in the world. We have been working with him for over a year on the problem of how best to handle iron carbonyl extracted from non-terrestrial ferrous metal alloys. Iron is the dominant constituent (40 to 93%) of native metals found in meteorites and in asteroidal metal fragments found in the lunar regolith. It is also the dominant metal in the metallic cathode deposits produced by electrolysis of molten lunar silicates, and is formed in large quantities and with a rather high degree of purity (99%) during the reduction of lunar ilmenite. Carbonyl extraction of iron from native Fe-Ni alloy has been demonstrated on a small scale in our own laboratory, but the disposition of the resulting iron pentacarbonyl vapor and liquid is unclear. Iron carbonyl CVD is never used for manufacture of strong metal components because of the tendency to precipitate a very fine-grained powder during thermal decomposition. This iron powder is of exceptional purity and of great metallurgical interest; indeed, it is the source of almost all the analytical-grade iron in the world market. However, the iron powder was something of a disappointment compared to the results of nickel tetracarbonyl CVD, which can quickly fill molds with bright, full-density, very strong nickel. Under similar circumstances, iron carbonyl leaves a mechanically weak, black deposit with a high carbon content. Jenkin, however, brought to our attention some unpublished laboratory experiments in which ammonia is added to the iron carbonyl to suppress carbon codeposition during production of analytical-grade iron powder. He suggested that we examine the effects of addition of ammonia during attempts to plate out tough iron films. Also, based on his own earlier experience, he suggested a similar experiment with water vapor as an additive. (All runs have added hydrogen and carbon dioxide).

The experiments with ammonia last year turned out promising results: two runs at 210 and 230°C with both ammonia and carbon dioxide added both produced bright, tough films, but unfortunately both developed stress cracks and partially peeled off the mandrel surface. But a run with water vapor, carbon dioxide and no ammonia looked even better, without spalling, and remained mirror-bright as long as deposition continued, but closer examination of the surface again shows

Table 5

Mass Payback Ratios

(one trip for fuel to 1977 VA; three-trip "Armada")
(all water returned on first trip used as fuel for new vehicles in LEO)

Earth Launch	Number of vehicles	dV out m/s	dV in m/s	Earth Arrival	Water LEO	Mass HEEO	MPBR
Nov 1990	4	5712	473	Nov 1995	400	0	7.0
Nov 1995	44	5712	316	Nov 2000	4	4400	29.1
Nov 2000	44	2322	1675	Nov 2005	4	7964	54.0
Nov 2005	40	2566	776	Nov 2010	4	11888	80.3

This model illustrates real multiple round trips to a single typical good asteroid, using trajectories from Lau and Hulkower (1985). All water returned by the first mission is used to fuel an "Armada" of vehicles delivered to LEO from Earth. The lifetime of each vehicle is three missions (15 years).

Original departure is from LEO and first return is to LEO. All returns to Earth use an asteroid-derived aerobrake with a mass fraction of 0.3 (to LEO) or 0.2 (to HEEO). Outbound propulsion for the first trip is H/O lifted from Earth; on subsequent trips it is H/O made by electrolysis of asteroidal water. Inbound propulsion is by solar thermal steam engine.

extensive cracking. The literature does not report reactions of ammonia with iron carbonyls to displace carbon monoxide (as happens with nickel carbonyl), and it is possible that the participation of ammonia begins with partial decomposition of ammonia and leads to nitriding of the iron surface, and hence to embrittlement.

Analyses of the metal film deposited without ammonia show about 3.9% oxygen and 1.6% carbon, nearly the same proportion as in carbon dioxide. Adsorbed and trapped carbon dioxide gas, not a bizarre alloy, may be responsible for this contamination. Jenkin suggests that deposition at lower pressures may alleviate this problem.

In general, carbon dioxide helps reduce the carbon content of the deposit, but increases the oxygen content. Water, at high concentrations, of course also is an important source of oxygen. Hydrogen suppresses the oxidation of the deposit by carbon dioxide, while helping keep the carbon content low. The impurity then approaches a C:O molar ratio of 1:2.

It seemed reasonable to try a run with only carbon dioxide as the carrier gas. The resulting deposit was bright, tough, adherent, and had a high deposition rate-- the best yet! Again, the«PG» impurity had the stoichiometry of carbon dioxide, and may be susceptible to removal by exposure to lower pressures or higher temperatures. A similar run with a little added hydrogen produced chemically similar results but had an even higher deposition rate. This year we had hoped to pursue these leads and begin experiments with mixtures of iron and nickel carbonyls, but the Akron fire department shut down Jenkin's laboratory in January 1992. It is reopening within the month, and we hope to resume experiments soon thereafter.

We are making clear progress toward the goal of direct deposition of iron with desirable physical properties. Experiments involving lower pressures, outgassing at higher temperatures, and codeposition of iron and nickel are all planned for Jenkin's laboratory. Here at SERC we are prepared to extend our experiments on carbon monoxide volatilization of ferrous metal alloys of interest in the space resources arena, including native lunar and asteroidal metals and metallic byproducts from schemes for lunar oxygen production. These experiments will require the services of a research staff member with a background in chemical research and experience in carbonyl handling. Fortunately, Dr. Muralidharan, who has played a major role in the development of schemes for platinum-group metal separations under SERC sponsorship, will be available to devote half his time to this project.

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