

# **VOLATILE PRODUCTS FROM CARBONACEOUS ASTEROIDS**

**CHARLES R. NICHOLS**

*Bose Corporation*

Samples from the Moon and most near-Earth asteroids are depleted in the volatile elements carbon and hydrogen. Only one class of asteroids is rich in these elements: carbonaceous asteroids. No carbonaceous asteroid has yet been sampled directly. Our knowledge of their composition is based on the study of carbonaceous meteorites. A wide variety of evidence suggests that near-Earth carbonaceous asteroids are the source of most carbonaceous meteorites. As about one third of the classified near-Earth asteroids appear to be carbonaceous, we can expect to find an abundance of volatile resources among the near-Earth asteroids. For space missions in the past, it has been necessary to bring all supplies from Earth. For the manned lunar base and Mars exploration missions of the future, we have the option of "living off the land." For example, space flight would be much less expensive if propellant were available in orbital fuel depots. Spacecraft could then be launched with empty tanks, dramatically reducing the payload mass and launch cost. Carbonaceous ore could be processed into propellant identical to that used by the space shuttle's main engines. When heated, the ore releases large quantities of water, carbon monoxide, and carbon dioxide. A fuel production plant could extract and process the water to provide a steady supply of hydrogen and oxygen propellant. Once in operation, the fuel plant becomes part of the growing infrastructure of the space economy. If we invest wisely in this infrastructure, it will yield tremendous economic benefits for decades to come. This chapter begins by discussing the economics of asteroid mining. Some simple volatile products are then identified. Production processes are suggested, with an emphasis on existing industrial practice. Finally, the mining environment is detailed, using the moons of Mars as well-studied examples.

## **I. INTRODUCTION**

Mankind's investment in space has grown steadily over the past thirty years. Space industrialization will become more desirable, and eventually an economic necessity, as this trend continues. These future space industries will need to find an economical source of materials. Carbonaceous asteroids will probably be the least expensive source of the volatile compounds needed for propellant and life support.

The utilization of native materials in space will require a large investment for the equipment which mines, processes, and transports them. Aerospace and government planners must decide when to begin investing in space-based

infrastructure. To do so, they will need information on what is known, what is possible, and what might be affordable.

### **A. The Market for Asteroidal Products**

The space resources literature continues to mature in its recognition of the importance of economic perspective. Cutler and Hughes (1985) identified low initial capital investment and quick payback as the prime requirements for economic feasibility of space mining. They identified propellants and metal plate, delivered to low Earth orbit (LEO) as the best products. Cutler also identified the design and development of mining processes as the biggest time bind (Gertsch et al. 1985). Cordell and Steinbronn (1988) found space resources pivotal for large-scale human operations in space, concluded that volatiles should be mined even if lunar oxygen were already in production, and agreed that keeping initial costs down was vital.

The cost of placing a pound of goods into LEO currently exceeds \$3000. Although designs for cheap launch services abound, they have not as yet been subjected to the rigors of the market. However, the economic viability of space resource utilization would probably survive the development of low cost launch technology. Leonard et al. (1987) concluded that a propellant mine at Phobos would be profitable as long as Earth-to-LEO launch cost exceeds \$250 to \$500 per pound.

Space-based industry can provide goods to LEO at a much lower cost than Earth-to-LEO under certain conditions. The cost of developing a new supply must be justified by a large demand (by weight) for the product. The cost of providing the product from space must be well below the cost of delivering it from Earth. Finally, the product must be easy to make from materials already present in space.

Space planners have attempted to predict the future needs of the space community, and have identified some volatile products which look promising. Volatiles in large quantities will be needed for life support for a permanently manned station. Propellants could be used for moving satellites, spacecraft, humans, and raw materials. Volatile reagents can be transported to other space factories and used to reduce the cost of their products, such as lunar oxygen and steel.

Volatile products for life support include water, oxygen, and nitrogen for humans, and carbon dioxide and fixed nitrogen for agriculture. Their availability allows a lifestyle in space characterized by abundance and self-sufficiency, as contrasted with the canned air, sponge bath, and reconstituted food lifestyle of the Apollo missions.

Cheap locally produced propellants could revolutionize the economics of space operations. Many space-derived propellant systems have been suggested. Medium-velocity systems include hydrogen, methane, kerosene, or methanol as fuel with oxygen as the oxidizer. A high-velocity option is superheated hydrogen monopropellant. The choice of medium- or high-velocity propellant depends on the mission's total velocity change ( $\Delta V$ ) before refuel-

ing. For missions with  $\Delta V$  under  $5 \text{ km s}^{-1}$  (typical of missions to near-Earth destinations), hydrogen/oxygen is the preferred propellant option. Its advantages include a mature technology base and wide availability of water as feed stock. For cometary resource missions, super-heated hydrogen is the recommended propellant option. To obtain a useful fuel to payload ratio on these high  $\Delta V$  missions, a very high exhaust velocity is required.

Volatile products which are potentially useful in metal processing are carbon monoxide, hydrogen and methane. Carbon monoxide is essential to the carbonyl process for low-temperature purification and deposition of iron and nickel. Hydrogen and carbon monoxide have been proposed as reducing agents for lunar ilmenite reduction. Methane has been suggested for the carbothermal reduction of lunar maria soils (Rosenberg et al. 1965).

## B. Sources for Volatiles

While carbonaceous asteroids are a high-grade source of volatiles, other non-terrestrial sources must also be considered. The Moon and many noncarbonaceous asteroids have ample oxygen and sulfur. Mars has abundant oxygen, sulfur, carbon, nitrogen, hydrogen and argon (Meyer and McKay 1989). These resources are discussed in detail elsewhere in this book.

Carbonaceous asteroids can be categorized by their orbital location in the solar system: main-belt asteroids, near-Earth asteroids (NEAs), short-period comets, and the Martian moons, Phobos and Deimos. Inferred composition is strongly correlated to the type of orbit. Composition is inferred based on reflectance spectrum, using a variety of taxonomic schemes (Tholen and Barucci 1989; Zellner 1979). This chapter uses "carbonaceous" in its most general sense as carbon-bearing. Current asteroid classification would include types P, D, RD, T, F, G and B as subclasses of type C, and thus probably rich in carbon and volatiles.

Main-belt asteroids include bodies up to 1000 km in diameter and their collisional fragments. The large ( $> 100 \text{ km}$ ,  $N = 195$ ) main-belt asteroids are 75% type C (Zellner 1979). The usual interpretation is that these type C bodies are carbonaceous. The composition of the main belt varies systematically from the inner to the outer edge, with type S dominating the inner belt and type C dominating the outer belt (Gradie and Tedesco 1982). Within the type C population, we can expect the composition to vary from thermally altered C3/C4 compositions in the inner belt to relatively pristine C1/C2 types in the outer belt.

The NEAs are small bodies ( $< 10 \text{ km}$ ) with a range of compositions spanning all common asteroid types. They are derived from a mixture of main-belt collisional fragments and burned-out short-period comets (Shoemaker et al. 1979). The total population of NEAs over 100 m diameter is estimated to be about 100,000 objects, with 150 or so currently known. A semi-automated telescope system at the University of Arizona called Spacewatch has considerably increased the discovery rate recently. The utility of NEAs as resources is heavily dependent on the economics of returning massive cargoes

from the candidate body. Dominating variables are fuel costs, launch window frequency, and round-trip time. If atmospheric braking can be used, many bodies can return cargo to Earth with extremely low fuel costs.

Short-period comets are small ( $< 10$  km) bodies which produce a characteristic tail of gas and dust when they are near the Sun. They (and the NEAs derived from them) may be composed primarily of volatiles. Short-period comet material is unlikely to be represented in meteorite collections due to its fragile structure. However, the volatile components are expected to include  $H_2O$ ,  $CO_2$ ,  $CO$ ,  $NH_3$ ,  $CH_4$  and a wide variety of organic compounds. A comet would be a first-class candidate for volatile resources. Unfortunately, the economics of returning cargo from a comet to Earth are nearly prohibitive. The very high return  $\Delta V$  produces an unacceptably low payload fraction, and is beyond the state of the art of atmospheric braking technology. For a few well-placed short-period comets, a combination of cheap propellant and atmospheric braking would allow economical recovery of high-value volatiles.

The Martian moons are black, very low density, small ( $\approx 10$  km), heavily cratered, and covered with dust. They have been well observed by four spacecraft with many types of instruments. Some question remains about whether they are actually carbonaceous. Although they resemble carbonaceous meteorites in density and color, they seem to contain little or no water of hydration at the surface (see Sec. VI.B). In any case, their proximity to Mars and excellent accessibility make them prime resource candidates. For the purposes of this review, they are considered to be carbonaceous asteroids.

### C. Target Selection

On Earth, mining sites are chosen based on simultaneous minimization of cost and risk. The same should be true in space. Ultimately, all estimates of cost and risk depend on having accurate knowledge of the site, and an accurate model of the operations to be located there.

The most economical way to estimate the cost and risk of mining on proposed ore bodies is to gather data through an extensive Earth-based observation program. Many bulk properties of asteroids can be determined by telescopic measurements. Among them are size, shape, mineral composition, orbit, rotation rate, orientation of the rotational axis, presence of a pulverized surface deposit, reflective albedo, and limited surface detail. From this data can be derived information about mass, density, surface gravity, probable composition, transportation costs, surface environment, and expected yield of volatile products.

To date, very few asteroids have been well characterized according to these criteria. The NEAs, which are among the most accessible asteroids, are also among the most poorly characterized. With NEAs, time is of the essence, because they can only be observed during rare close approaches to Earth. The solution is to dedicate a telescope with the necessary instruments to the task of immediately following up new discoveries. A large number of accessible asteroids should be characterized. The best candidates could then be selected

and exhaustively studied.

#### D. Prospecting for Resources

When the target characterization and selection process reaches a consensus, it is time to send a prospecting mission. Prospecting at such remote bodies is so expensive that it will probably be confined to a single mission. The prospecting craft should include an orbiter, a lander, and penetrators. The orbiter allows detailed surface mapping and the selection of candidate sites. The lander allows tests of various means of ore acquisition and processing, plus evaluation of ore composition. A cluster of small penetrator probes allows subsurface sampling, plus soil depth and rock strength experiments. With this data in hand, a go/no-go decision can be made for the body, a site can be selected, and equipment design can begin.

## II. DESIRED VOLATILE PRODUCTS

In this section, "volatile products" refers to simple compounds of hydrogen, oxygen, carbon, sulfur and nitrogen, which could be produced from carbonaceous ore (see Table I). "Desired" indicates that, in the author's judgement, they are likely to be useful in large quantities for the support of some ongoing space project.

**TABLE I**  
Properties of Volatile End Products and Byproducts<sup>a</sup>

Molecule	mp, °C	bp, °C	Liq g/cc	Gas g/L	Primary Use
H <sub>2</sub>	-259	-253	0.0700 <sup>bp</sup>	0.0899 <sup>0</sup>	Fuel
N <sub>2</sub>	-210	-196	0.808 <sup>bp</sup>	1.251 <sup>0</sup>	Air
CO	-199	-192	0.814 <sup>bp</sup>	1.250 <sup>0</sup>	Metallurgy
O <sub>2</sub>	-218	-183	1.149 <sup>bp</sup>	1.429 <sup>0</sup>	Propellant, Air
CH <sub>4</sub>	-182	-164	0.466 <sup>bp</sup>	0.717 <sup>0</sup>	Fuel
CO <sub>2</sub>	-57 <sup>5atm</sup>	-78 <sup>subl</sup>	1.101 <sup>-37</sup>	1.977 <sup>0</sup>	Agriculture
H <sub>2</sub> S	-85	-60	0.993 <sup>bp</sup>	1.539 <sup>0</sup>	Metallurgy
NH <sub>3</sub>	-78	-33	0.682 <sup>bp</sup>	0.771 <sup>0</sup>	Agriculture
SO <sub>2</sub>	-73	-10	1.50 <sup>-20</sup>	2.92 <sup>0</sup>	Refrigerant
Ni(CO) <sub>4</sub>	-25	+43	1.32 <sup>17</sup>		Metallurgy
SO <sub>3</sub>	(+17)	+45	1.97 <sup>20</sup>		To make H <sub>2</sub> SO <sub>4</sub>
CH <sub>3</sub> OH	-94	+65	0.791 <sup>20</sup>		Fuel
NH <sub>4</sub> OH	-77	(+100)	0.90 <sup>25</sup>		Agriculture
H <sub>2</sub> O	+0	+100	1.000 <sup>mp</sup>		Life support
Fe(CO) <sub>5</sub>	-21	+103	1.457 <sup>21</sup>		Metallurgy
H <sub>2</sub> O <sub>2</sub>	-0	+150	1.407 <sup>25</sup>		Oxidizer
H <sub>2</sub> SO <sub>4</sub>	+10	+290	1.841		Metallurgy

<sup>a</sup> Data from Weast 1983; Windholz 1983. Superscript gives temperature at which the measurement was made. NH<sub>4</sub>OH is 29% NH<sub>3</sub> (by weight) in water.

## A. Water

Water seems ideal as a first product for industry in space. It is produced by low temperature pyrolysis of C1 or C2 ore, along with carbon dioxide, from which it is easily separated. Water is useful in large quantities for life support. On manned missions, it is an efficient shield against solar flares and cosmic rays. It can be converted (by electrolysis or thermolysis) into hydrogen and oxygen, which are also among the most useful of products. It is also a useful solvent and reagent in many industrial processes. Water can be easily transported as a liquid or as a solid. Large solid blocks could remain exposed to vacuum for years with minor loss, thus avoiding the cost of containers.

## B. Hydrogen

Hydrogen's potential usefulness has been stifled on Earth, due to the danger of ignition in an oxygen-rich atmosphere. In space it is likely to find many new uses. Its extremely low molecular weight makes it ideal for a number of applications. For example, it has the highest mean velocity of any molecule at a given temperature, making it the ideal monopropellant for thermal rockets. It also has by far the highest specific heat of any gas, making it a good candidate for a heat transfer medium. Hydrogen is also a useful reagent, especially for lunar production of oxygen and metals (Ness et al. 1991). The hydrogen in such reactions is converted to water, which can be efficiently recovered and recycled.

Hydrogen is as unwieldy as it is useful. Gaseous hydrogen is uneconomical to store, because the container far outweighs the gas. Liquid hydrogen is somewhat cheaper to store, but requires continuous refrigeration to prevent boil-off, even in the space environment. Hydrogen is also expensive to liquefy, due to its extremely low boiling point, its very low inversion temperature (above which Joule-Thompson expansion produces a rise in temperature, instead of lowering it), and the need to convert ortho-hydrogen to para-hydrogen (Neary 1983). Hydrogen should therefore be produced at the site of use whenever possible, to avoid storage.

When it must be transported, hydrogen should first be converted to a carrier compound such as water, methane, or ammonia. The carrier compound should be easy to produce, easy to recover hydrogen from, have a high boiling point, have a high weight of hydrogen per volume, and contain only useful elements available in space. For comparison, hydrogen storage density in each liquid at its boiling point is:  $\text{H}_2 \approx 0.070$ ,  $\text{H}_2\text{O} \approx 0.112$ ,  $\text{CH}_4 \approx 0.117$ , and  $\text{NH}_3 \approx 0.121 \text{ g cm}^{-3}$ .

Water is the perfect hydrogen carrier for hydrogen/oxygen propellant. The ratio of hydrogen to oxygen in water is nearly ideal for propellant use. The liquefaction of hydrogen could be avoided entirely by designing rockets which electrolyze water, and immediately burn the gases. The tiny rocket engine would produce a steady low thrust, with only water and electricity as inputs.

Methane is a more appropriate carrier than water if the end-use site is

the Moon, because the Moon already has plenty of oxygen, but is deficient in carbon. During low-thrust spaceflight, methane can be decomposed to hydrogen, which is burned immediately, and graphite, which is stored (see Sec. III.F). When a high-thrust burn is required, the methane can be burned directly.

Ammonia is the best hydrogen carrier in terms of hydrogen storage density. Its use is hampered by the low abundance of nitrogen in typical carbonaceous asteroids. Ammonia may occur in abundance in comet nuclei and burned-out comets, however.

### C. Oxygen

Oxygen is useful both for propulsion and for life support. As an oxidizer for propulsion, there is no good alternative. The other oxidizers used in rocketry (chlorates, nitric acid, nitro compounds and nitrogen tetroxide) have lower performance and contain elements that are scarce in carbonaceous meteorites. Hydrogen peroxide is sometimes used as an oxidizer, but also has low performance, and is hard to make in space. Water seems an ideal noncryogenic carrier for oxygen. It is simple to make as well as to decompose, is 90% oxygen by weight, and requires minimal tankage.

### D. Carbon

Carbon is useful as a reagent and as a refractory material. Its use in steel-making is well established on Earth. It is likewise used in refining high-energy elements such as silicon, aluminum, magnesium and calcium. Its use as a reducing agent in space will require improvements in carbon dioxide recycling technology, however. Carbon recycling has not been developed on Earth due to the very low cost of industrial carbon. A means of reducing  $\text{CO}_2$  to CO using stabilized zirconia at  $900^\circ\text{C}$  has been demonstrated in the laboratory (Erstfeld et al. 1979). On the Moon, carbon can be converted to carbon monoxide using locally produced oxygen. Carbon monoxide has been suggested as a reducing agent for oxygen production from lunar ilmenite (Zhao and Shadman 1991). It could also be used to win the 0.2 to 0.5% of metallic iron in lunar regolith (Agosto 1981) via the carbonyl process.

### E. Carbon Monoxide

Carbon monoxide is a possible export from a carbonaceous to a non-carbonaceous asteroid. The choice of whether to export carbon or carbon monoxide is a matter of economics. Carbon monoxide is 57% dead weight if oxygen is available at the destination. If the transportation cost is small, or the conversion of carbon to the monoxide at the site of use is inconvenient, then carbon monoxide is the preferred export.

Carbon monoxide is a cryogenic gas, and therefore costly to store. Metal carbonyls are excellent carrier compounds, being solid below  $-40^\circ\text{C}$ . Iron and nickel carbonyls contain 70% carbon monoxide by weight, and are easily produced and decomposed.

Most types of noncarbonaceous asteroids are expected to be rich in nickel-iron (NiFe) metal. Carbon monoxide is a nearly ideal reagent in the processing of NiFe, via the carbonyl process. The process works at low temperatures, requiring little power or cooling equipment. It works at modest pressures, thus allowing an inexpensive reaction vessel. Best of all, it produces finished metal goods from unrefined NiFe in a single process step (Lewis and Nozette 1983; Lewis et al. 1988).

The carbonyl process consumes very little carbon monoxide. The only loss is the tiny percentage remaining in the ore and the metal product. Thus a very large foundry could operate with a small input of makeup gas. This is actually an argument against mining asteroids for carbon monoxide alone, because the amount needed could be brought from Earth at reasonable cost. However, because carbon monoxide will be a by-product of other processes, its production is essentially free.

#### **F. Miscellaneous Fuels**

A wide variety of fuels for propulsion can be produced from carbonaceous ore. This subsection will briefly mention some of the more promising fuels. Hydrogen has already been discussed in Sec. II.B.

Methane is a high specific impulse fuel which is rarely used currently. As methane and oxygen boil only 20°C apart, the two gases can be liquefied by the same equipment.

Kerosene is a fuel with a long history in rocketry. It has a specific impulse somewhat lower than methane, and is more difficult to produce, but does not require refrigeration.

Methanol has a still lower specific impulse, but is rather easier to produce than kerosene. Like kerosene, it requires no refrigeration.

Carbon monoxide has been suggested as a fuel in the context of propellant production on Mars, assuming no water is available (French 1989). Carbon monoxide/oxygen rockets have a low specific impulse compared to conventional systems. However, if a carbonaceous asteroid contains carbon but no water, CO/O<sub>2</sub> could become the propellant system of choice for local use.

Magnesium metal and magnesium hydride are very high energy fuels. They could be made from epsomite (MgSO<sub>4</sub>·7H<sub>2</sub>O), which is easy to extract and purify, and comprises 5 to 15% of C1 ore (Gaffey and McCord 1979). The disadvantage in using these fuels is that they produce high molecular weight (and therefore low mean velocity) oxides. The specific impulse of these fuels could therefore be improved by adding water, hydrogen, or methane to the exhaust (Mul et al. 1990).

#### **G. Rare Gases**

A number of gases which are present in low or trace quantity in carbonaceous matter should be briefly mentioned because of their high desirability as by-products. These rare gases include nitrogen, the halogens, and the noble



gases.

Nitrogen comprises 0.1 to 0.3% of C1 and C2 ore (Moore 1971) and 1 to 3% of the organic matrix material (see Table II). It is released primarily as  $N_2$  gas during pyrolysis of these materials (Wszolek et al. 1973), and could be recovered as a by-product. Cometary materials are likely to contain much higher percentages of nitrogen.

The primary market for nitrogen is as an inert filler gas in breathing air. While other gases (e.g., helium) have been used for such purposes, no other inert gases are available in like quantity in near-Earth space. As it is likely that any substitution would be noticed by the residents, nitrogen is the natural choice if it is available.

If an abundant source of nitrogen were available (from a comet for example) nitrogen-based propellants would be economically viable. Hydrazine ( $N_2H_4$ ) is a widely used monopropellant which is catalytically decomposed to generate thrust on demand. Nitrogen tetroxide ( $N_2O_4$ ) is a noncryogenic storable oxidizer, useful in rocketry as a substitute for liquid oxygen.

The halogens chlorine and fluorine are present in carbonaceous meteorites to the extent of  $\sim 0.03\%$  and  $\sim 0.02\%$ , respectively (Reed 1971). The similarity in concentration from C1 to C4 indicates that moderate heating does not volatilize halogens. Polymeric carbon extracted from carbonaceous meteorites by HF/HCl digestion contains  $\sim 1\%$  each of F and Cl (Hayes 1967), indicating that most of the halogen resides in this fraction and could be released during high-temperature pyrolysis. The halogens are of interest mainly as reagents.

The noble gases helium, neon and argon represent a highly variable resource. Solar-wind implantation seems to be the primary source of the noble gases in gas-rich meteorites (Heymann 1971). Their uses include pressurizing gas for liquid propellants, cryogenic coolant, and inert atmospheres for high temperature processing.

The lunar regolith can be used as a rough guide to the upper limits of solar-wind implantation in carbonaceous asteroids. These atoms are implanted at a shallow depth ( $< 100\mu m$ ), and should be released by moderate heating. The maximum concentrations seen in lunar regolith are  $N \approx 200$  ppm,  $Cl \approx 200$  ppm,  $F \approx 400$  ppm,  $He \approx 100$  ppm,  $Ne \approx 10$  ppm and  $Ar \approx 10$  ppm (Haskin and Warren 1991). The finest material is the richest in solar wind gases.

### III. LESSONS FROM INDUSTRIAL CHEMISTRY

Before any large-scale engineering project can begin, it must receive financial approval. Investors require proof that the project is a good investment, and part of the proof is a comprehensive plan for minimizing risk. Accountants must be pessimistic precisely because engineers cannot help being optimistic. Every new technology has unforeseen bugs that need to be worked out. A project which relies heavily on new technology will limp through life and die in shame.

**TABLE II**  
Elemental Composition of Ash-free Organic Phases<sup>a</sup>

	C	H	O	N	S	Tot.	C/H	Reference
C1 meteorite	73.6	4.6	10.3	1.66	7.23	97.4	15.9	Hayes 1967
C2 meteorite	78.	3.1	13.	1.7	4.2	100.	25.	Zinner 1988
Oil Shale, KY	82.0	7.4	6.3	2.3	2.0	100.	11.1	Smith and Jensen 1987
Oil Shale, UT	80.5	10.3	5.8	2.4	1.0	100.	7.8	Smith and Jensen 1987
Bituminous, PA	82.4	5.6	9.0	1.6	1.3	100.	14.6	Smoot 1979
Anthracite	89.4	3.8	4.6	1.1	1.1	100.	23.6	Smoot 1979
Heavy Petroleum	85.3	11.0	0.5	0.4	2.8	100.	7.7	
Light Petroleum	85.7	12.7	0.3	0.2	1.1	100.	6.8	

<sup>a</sup> All compositions are weight percent. C1 is Orgueil, water- and solvent-insoluble fraction only. (Content includes 1.28% Cl, 1.31% F; may be contamination.) C2 is Murchison. C1 and C2 organic phases are obtained by HCl/HF digestion of inorganic phases. Some insoluble mineral matter remains, so the above data have been recalculated on an ash-free basis. For a discussion on the nature and origins of the organic matter in carbonaceous meteorites, see Cronin et al. (1988). Petroleum data are for comparison only; derived by author from data in Perry and Chilton (1973) and Grayson and Eckroth (1982).

Asteroid mining seems at first glance to have no established technological base to build upon. But while the physical environment is unprecedented, the raw materials bear a useful similarity to some earthly raw materials. The chemical engineering for processing asteroids should draw from existing technology, and thereby reduce the overall project risk.

On Earth, the technology for converting raw materials into volatile fuels is well developed. Coal can be gasified to  $H_2 + CO$ , hydrogenated to a mixture of hydrocarbons, or pyrolyzed to coal tar and coke. Petroleum is distilled to remove light hydrocarbons, and the residue is either cracked to yield more light hydrocarbons, or pyrolyzed to yield heavy hydrocarbons plus coke. Oil shale is pyrolyzed to give a mixture of light and heavy hydrocarbons, leaving a substantial carbonaceous residue which is discarded (Allred 1982).

The choice of technology is dominated by the carbon:hydrogen ratio (see Table II). A feedstock with a low ratio will be easily distilled. A high ratio will produce little or no volatile fraction. For petroleum  $C/H \approx 6-8$  (by weight), for oil shale  $C/H \approx 8-13$ , and for coal and carbonaceous meteorites  $C/H \approx 13-25$  (see Table III). Experiments on carbonaceous meteorites confirm that little organic vapor is released during vacuum pyrolysis. Furthermore, pyrolysis produces a complex mixture of compounds, including many with limited utility in space. Thus oil shale and petroleum technology are generally of little use in processing carbonaceous asteroids.

**TABLE III**  
C/H Ratio vs Yield of Volatiles<sup>a</sup>

C/H	Volatiles	Source of Coal
12.7	44.8%	Church Mine, UT, USA (bituminous)
13.7	39.9%	Illinois, USA (bituminous)
14.6	36.6%	Pittsburgh, PA, USA (bituminous)
16.4	28.9%	Pittsburgh (high-volatile bituminous)
19.6	16.3%	Sewell (medium-volatile bituminous)
23.6	8.8%	(low-volatile anthracite)
C/H	Volatiles	Source of Oil Shale
7.8	69. %	Garfield County, CO, USA
8.4	60. %	Glen Davis, Australia (Cannel Seam)
9.8	53. %	Ermelo, Transvaal, South Africa
11.1	33. %	New Albany, KY, USA
11.5	26. %	Glen Davis, Australia (Top Seam)
12.8	13. %	Pictou County, Nova Scotia, Canada

<sup>a</sup> C/H ratios and % Volatiles are by weight. Oil shale "volatiles" are the percentage of organic carbon converted and recovered as oil during Fischer assay. Coal "volatiles" are the percentage of the coal's weight (as mined) which is released as vapor during vacuum pyrolysis. Water is not included. Coal data are from Smoot (1979). Oil shale data are from Smith and Jensen (1987).

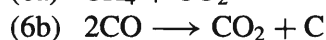
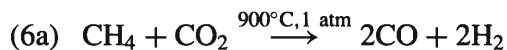
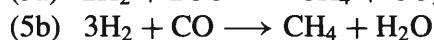
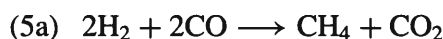
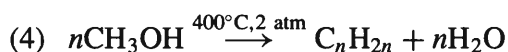
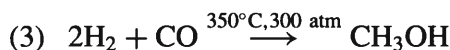
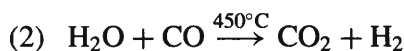
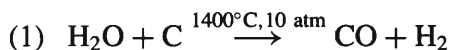
A more useful model for processing carbonaceous material is coal gasification technology. This technology should be tested on carbonaceous meteorite material. Of course, coal and carbonaceous chondrite have significant differences in mineral content. Also, economic constraints are different at a mining site in space. We can therefore expect some processes to require significant modification or even be totally unworkable. These processes are presented only as a starting point for a more extensive investigation.

An excellent introduction to modern coal technology can be found in *Riegel's Handbook of Industrial Chemistry*. The chapter on coal technology (Funk 1983) covers the conversion of carbon plus water to carbon monoxide plus hydrogen, and then to synthetic petrochemicals. The chapter on industrial gases (Neary 1983) discusses the production, purification, and liquefaction of hydrogen. The chapter on synthetic organic chemicals (Haberstroh and Collins 1983) details the synthesis of methanol from carbon monoxide and hydrogen.

The remainder of this section is a review of coal processing reactions which appear to be both useful and workable. A summary of the reactions is given in Table IV.

**TABLE IV**  
Industrial Processes to be Tested for Use in Space

- 
1. Synthesis gas via coal gasification (O<sub>2</sub> is also added)
  2. The watergas shift, converting CO to H<sub>2</sub> (iron oxide catalyst)
  3. Methanol production from synthesis gas (zinc oxide catalyst)
  4. Alkenes via Mobil's M-gasoline process (zeolite catalyst)
  5. Methane production from synthesis gas
  6. Conversion of methane to hydrogen and carbon (Ni catalyst)



### **A. Synthesis Gas**

Coal gasification is widely used to convert coal into useful industrial gases. The coal reacts with water, at 1000 to 1800°C and 1 to 100 atm pressure. Oxygen is added to generate the process heat which drives the reaction. The exit gases are cooled, separated from liquid and solid by-products, and scrubbed to remove acid gases. The product is a mixture of carbon monoxide and hydrogen gas, known as synthesis gas.

If hydrogen alone or carbon monoxide alone is the desired product, the gases can be separated cryogenically or by scrubbing. More commonly, the gas mixture is modified by the watergas shift, and used to synthesize other chemicals. The three most common end-products are methane, methanol and synthetic petroleum.

### **B. The Watergas Shift**

The watergas shift is an important subsidiary process in reactions involving synthesis gas. It is used to optimize the carbon monoxide to hydrogen ratio for increased yields. Water is added to the synthesis gas just downstream of the gas generator. The amount of water added must be carefully controlled to obtain the desired CO:H<sub>2</sub> ratio. The water reacts exothermically with the carbon monoxide to produce carbon dioxide and more hydrogen. The carbon dioxide is then removed in the scrubber with the other acid gases.

### **C. Synthetic Methanol**

Nearly all methanol is currently produced from synthesis gas. The synthesis gas is compressed to 300 atm, heated to 350°C, and reacted in contact with a zinc oxide/chromium oxide catalyst. Work is proceeding on a reduced-pressure process, which would allow a much less massive reactor.

### **D. Synthetic Gasoline**

Mobil's M-gasoline process converts methanol into high-octane gasoline. The gasoline retains about 95% of the methanol's fuel energy, but only 44% of its weight. The product, a mixture of low-boiling alkenes, can be used without fractional distillation.

### **E. Synthetic Methane**

While most of the world's methane supply is natural, significant quantities are produced from coal via synthesis gas. A plant in Beulah, North Dakota produces 700,000 tons per year of synthetic methane from low-rank coal. The highly exothermic reaction produces methane, carbon dioxide and water. The water is removed by condensation. The carbon dioxide is removed by scrubbing with water at 30 atm pressure. The last traces of each are removed by molecular sieves if the methane is to be liquefied.

### **F. Methane Decomposition**

If methane is used as a hydrogen carrier, a means must be devised to recover

the hydrogen. A reaction used for making synthesis gas from methane can be pressed into service. Carbon dioxide is reacted with the methane at 900°C to produce carbon monoxide and hydrogen. The exit gases are cryogenically separated. The hydrogen is stored or used immediately, and the unreacted methane and carbon dioxide are recycled. The carbon monoxide is heated with a catalyst, causing it to disproportionate into graphite, which is stored, and carbon dioxide, which is returned to the first step. The net reaction is  $\text{CH}_4 \rightarrow 2\text{H}_2 + \text{C}$ .

#### IV. HOW TO PROCESS A CARBONACEOUS ORE

This section proposes some processes for use with carbonaceous ore, based on current industrial practice. These processes should be studied, tested and improved, as discussed in the next section.

*Process 1: Water Production.* The crushed ore is placed in a closed vessel and heated to 400°C (Hashimoto et al. 1979) with steam at 1 atm pressure. The vapor is removed, cooled to 10°C, and solids and gases are separated from the liquid water. The water (some of which is recycled to the first step) is outgassed briefly in vacuum to remove dissolved gases, and placed in storage.

*Process 2: Hydrogen/Oxygen Production.* Water from Process 1 is electrolyzed or thermolyzed. The two resulting gas streams are cooled to condense water vapor, then dried further with molecular sieves. The gases are liquefied and placed in storage. The process should be located near the point of use. Many designs for this process have appeared in the literature (Bock and Fisher 1978; Heald et al. 1978; Schuster et al. 1986).

*Process 3: Carbon Monoxide Production.* The crushed ore is placed in a vessel with carbon monoxide gas. The gas serves as a nonreactive heat transfer medium to more quickly heat the ore. The vessel is heated until gas begins to evolve. The resulting gas phase ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and organics) is then continuously flushed out with preheated CO to prevent it from reacting with the fixed carbon. When gas ceases to evolve, the temperature is raised to 1000°C. The fixed carbon and magnetite in the ore then react to form carbon monoxide and iron metal (Hashimoto et al. 1979; Gooding 1975). The exit gases are cooled to -150°C, and the condensed impurities ( $\text{S}_8$ ,  $\text{SO}_2$ , and  $\text{Na}_2\text{O}$ ) are removed. The CO is then liquefied and placed in storage.

*Process 4: Methane/Oxygen Propellant Production.* Crushed ore is heated with steam to 1000°C in a closed vessel. The volatiles are drawn off and worked up to give purified  $\text{H}_2\text{O}$ ,  $\text{H}_2$  and CO. The water is electrolyzed as in Process 2, with only the oxygen placed in cryogenic storage. The hydrogen and the carbon monoxide are sent to a methanator. The resulting methane is purified, liquefied and placed in storage.

#### V. TESTING A PROPOSED PROCESS

This section discusses techniques for testing the processes proposed for car-

bonaceous ores. A new process for use on Earth can be tested at lab-scale and pilot-scale with real ore samples. Unfortunately, the small supply of C1/C2 meteorites and the high cost of increasing the supply make this testing approach impractical for carbonaceous ore.

Thorough testing of a process is not only much more difficult with asteroidal resources. It is also much more important. The cost of adding to or modifying the equipment, once delivered, will be prohibitive. Therefore, every effort must be made to fully utilize existing process simulation methods, to develop effective new methods, and to design intelligent and flexible hardware.

### **A. Computer Simulation of Ore Processing**

Computer modeling of carbonaceous ore processing has just begun recently (Ganguly and Saxena 1989; Bose and Ganguly 1991). It would be desirable to use such methods to predict the products of pyrolyzing or gasifying carbonaceous ore. Researchers must simultaneously refine their models of carbonaceous mineralogy and thermodynamic parameters. Once these milestones are achieved, however, computer modeling will allow rapid testing, comparing, and optimization of processes. This area of study is vital to the future of space resources.

### **B. Processing of Carbonaceous Ore Simulant**

Some form of simulant is clearly desirable for pilot-scale testing. Lunar simulants have been developed (Weiblen et al. 1990) and successfully employed in processing experiments (see, e.g., Ness et al. 1991; Garvey and Magoffin 1991). Carbonaceous meteorite simulants do not currently exist, and may not be possible with current technology. Carbonaceous materials are microcrystalline to amorphous, contain many nonsilicate phases, and are not in equilibrium. A realistic near-term research goal would be the use of computer models to design limited simulants. These materials would be able to mimic the response of carbonaceous ore to a limited range of processing conditions.

### **C. Micro-Scale Experiments on Carbonaceous Meteorites**

Experiments on carbonaceous meteorites have concentrated on scientific, rather than engineering, problems. The most useful for present purposes involve pyrolysis. Stepwise pyrolysis with gas chromatography (GC)/mass spectroscopy (MS) was performed on C3 Allende (Levy et al. 1970) and on C3 Allende, C2 Murchison and C2 Murray (Studier et al. 1972). Slow pyrolysis experiments with MS include C3 Allende (Gooding 1975), C2 Murchison (Hashimoto et al. 1979), C3 Allende and C2 Murchison (Simoneit et al. 1973), and C2 Murray (Wszolek et al. 1973). Extraction with organic solvents was also used with GC/MS (Studier et al. 1972) and with absorption and fluorescence spectrometry (Hodgson and Baker 1969).

An important goal of future experiments is to provide verification of computer models. Experiments should be designed to exercise a wide range

of reaction conditions. Temperature should be varied from  $-200^{\circ}\text{C}$  to  $1600^{\circ}\text{C}$ . Pressure should be varied from vacuum to 100 atm. Aqueous pH should vary from 0 to 14. Strong oxidizing and reducing, as well as neutral, environments should be tested. The goal is to provide reference experiments which create confidence that all the model parameters have been thoroughly tested.

More specifically, experiments should measure the composition of: water or acid extracts as a function of temperature, pressure and contact time; products of contact with a hydrogen, oxygen, steam, carbon monoxide, or carbon dioxide atmosphere as a function of temperature, pressure and contact time; and the reduced metal phase as a function of pyrolysis temperature and pretreatment conditions. This is far from an exhaustive list.

#### **D. Pilot-Plant Testing**

As the process approaches implementation, scale-up will be necessary. A pilot plant should be built and tested in Earth orbit. At first it will process simulants. When it is working reliably with simulants, it is time to feed it real ore. A large-scale sample return is probably not economically practical. Therefore, it will be necessary to send the pilot plant to the mining site. The delivered pilot plant should be highly reprogrammable and reconfigurable so that the process can be adapted to unforeseen problems. If Earth-based mining experience is any guide, there will be plenty of unforeseen problems.

### **VI. THE MOONS OF MARS AS ORE BODIES**

It may seem unwarranted to include the satellites of Mars in a discussion of carbonaceous asteroids, as they are not technically asteroids. They are, however, quite asteroid-like, in size, shape, and rotational rate (Veverka and Thomas 1979). They may even have been formed in the asteroid belt, and later captured by Mars (Hartmann 1987). In any event, they are potential sources of volatiles, and seem to be carbonaceous.

The Martian moons, Phobos and Deimos, are of special interest as resources because of their location. In addition to their value as bases for the exploration of Mars, they are more accessible more often than any known asteroids (O'Leary 1985). Their proximity to Mars has also allowed them to be studied by four spacecraft at close range. Even after the upcoming asteroid flyby missions, they will remain the best understood small bodies in the solar system.

This section presents both data and speculation on the nature of the mining environment. Hard data has been obtained not only from the numerous spacecraft encounters, but also from Earth-based telescopes. The speculation is informed by observations of the other bodies in the solar system, the study of meteorites, and computer models of the micro- and macroscopic processes involved in the solar system's formation.

The level of our current knowledge is much less than a mining geologist would like, but much more than might be expected. The loss of PHOBOS 1



and 2, the only two spacecraft ever dedicated to the study of an “asteroid,” is deeply felt.

### A. Summary of Observations

The data from the two Viking Orbiters provided many details on the Martian moons (for a review, see Veverka and Thomas 1979). The two moons are similar in color, size, shape, surface gravity, density and orbit. Their color is black, with 4% reflectance and a nearly featureless spectrum. Their size is 21 km (Phobos) and 13 km (Deimos) in mean diameter. Their shape is roughly ellipsoidal ( $1.5 \times 1.3 \times 1.0$ ), and their surfaces are saturated with craters. Their surface gravities are  $\sim 0.0005$  Earth gravity. Their density is  $\sim 2 \text{ g cm}^{-3}$ . Their orbits are circular in the plane of Mars' equator. Craters on Phobos are distinct, while craters on Deimos are often nearly obliterated by ejecta.

### B. Composition

The composition of the moons is not firmly established. The author favors the hypotheses of Hartmann (1987,1990). He proposes that an icy carbonaceous asteroid formed in the cold outer belt, and was subsequently captured by Mars. An early impact split the body, creating two moons whose orbits then evolved separately. Since then, the surface material has suffered many impacts, causing loss of volatiles. The surface material has been extensively reworked, because most impact ejecta go into orbit around Mars and are eventually redeposited. The near-surface ice has been lost, both by impact vaporization (Grimm and McSween 1989) and by slow sublimation (Fanale and Salvail 1990). Ice remains at depths of  $\sim 500$  m at the equator and  $\sim 50$  m at the poles.

Based on laboratory and spacecraft measurements of spectral reflectance, the proposed meteorite analogs are C1 or C2 (Pang et al. 1978; Pollack et al. 1978; Veverka 1978) and shock-blackened ordinary chondrite. It now appears that no known material matches the moons if spectra in the ultraviolet, visible and infrared are included (Britt and Murchie 1991).

C1 and C2 meteorites are composed primarily of water-bearing phyllosilicates (clays), which show a characteristic  $3 \mu\text{m}$  absorption feature in the laboratory. The  $3 \mu\text{m}$  feature has also been observed on many type C asteroids, indicating that they are hydrated. This feature is weak or absent in spectra of Phobos' surface obtained by the Phobos 2 spacecraft (Bibring et al. 1989). Thus C1 and C2 do not seem to be good model compositions for Phobos.

The arguments against a type C3 or ordinary chondrite composition hinge on their high density. Phobos has a mass of  $1.08(\pm 0.01) \times 10^{19} \text{ g}$  (Avanesov et al. 1989) and a volume of  $5.68(\pm 0.25) \times 10^{18} \text{ cm}^3$  (Duxbury, personal communication). Its calculated density is therefore  $1.90(\pm 0.09) \text{ g cm}^{-3}$ . By comparison, densities are typically 2.2 for C1, 2.6 to 2.9 for C2, 3.4 for C3, and 3.3 to 3.9 for ordinary chondrites (Mason 1966). If Phobos were made of ordinary chondrite, the bulk density would require that nearly the entire

body consist of uncompacted rubble, with 40–54% mean void volume. Logic argues against such a high void content in a compaction environment characterized by constant bombardment and 100 to 600 g cm<sup>-2</sup> (Thomas et al. 1986) internal gravitational pressure.

It should be noted that such high void content does occur naturally under special conditions. Regolith at the lunar surface and well-sorted sediments on Earth have similarly high void content. However, the density of lunar regolith rises rapidly with depth (due to compaction processes), and there is no plausible mechanism for creating well-sorted rubble on Phobos.

Observations also argue against such a high void content. “On Phobos, patterns of grooves and ridges suggest a moderately competent internal structure,” rather than a rubble pile (Thomas et al. 1986). Also, the near-surface material is strong enough in many places to produce large blocks of coherent crater ejecta.

Having found difficulties with all of the proposed meteorite analogs, we must consider the possibility that Phobos is composed of some material not represented in meteorite collections. The material is similar in density and spectral reflectance to C1 and C2 chondrite but contains little or no hydrated silicate. Either the silicates never hydrated, or they did hydrate and then were dehydrated.

Theoretically, the silicates in an icy asteroid which has remained forever frozen should be anhydrous, while silicates in contact with liquid water for ~1000 yr should be completely hydrated (Grimm and McSween 1989). This claim is supported by recent observations that most type C asteroids in the warm inner belt show absorption at 3 μm, while those in the cold outer belt do not (Lebofsky et al. 1990; Jones et al. 1990).

The author therefore proposes C1 plus ~10% water ice as the initial composition of the Martian moons. This prediction is consistent with the observed density of Phobos. Its high content of volatiles would cause it to break up quickly in an encounter with Earth’s atmosphere, explaining the lack of corresponding meteorites on Earth. The surface dust would be low in volatiles due to repeated impact, but would retain fixed carbon. The interior would be cracked rather than shattered, and would retain most of its primordial ice.

### **C. The Mining Environment**

Phobos and Deimos have been observed from Mariner 9 (1971), Viking Orbiters I and II (1976), and the Soviet craft Phobos 2 (1988) as well as from Earth. The results from these observations which are relevant to mining operations are summarized here.

The rotational axes of Mars and its moons are inclined 25° to the ecliptic. The moons each keep one hemisphere permanently facing Mars (Burns 1978). Sunlight on the inner faces is blocked by Mars once per orbit near the equinoxes, but not near the solstices. Phobos is eclipsed by Mars more frequently and during more of the year than Deimos.

Sunlit surfaces are exposed to solar-wind protons at  $700 \text{ km s}^{-1}$ . During eclipses, the surface is exposed to Mars' plasma tail of atomic oxygen at  $150 \text{ km s}^{-1}$  (Lundin et al. 1989; Rosenbauer et al. 1989). The entire surface is subjected to micrometeorites and cosmic rays. It should be noted that the Moon is subjected to similar particle fluxes.

The effective gravitational force on the moons' surfaces is highly variable with position. Four factors contribute to the field: gravitational attraction to the moon's center of gravity, gravitational anomalies due to the moons' nonspherical shape, centrifugal force of their rotation and their orbit around Mars, and tidal forces from Mars. On Phobos, all four factors are of the same order of magnitude (Davis et al. 1981; Dobrovolskis and Burns 1980).

The surface temperature of both moons has been modeled by computer (Kührt and Giese 1989; Giese and Kührt 1990). The model's predictions were verified by the Phobos 2 spacecraft (Ksanfomality et al. 1989). Surface temperature extremes are  $+40^\circ\text{C}$  at the equator and  $-210^\circ\text{C}$  at the poles. The axial tilt causes large annual temperature swings as a function of latitude. The orbital eccentricity also causes large annual temperature swings, as a function of solar distance. The direction of axial tilt when the Sun is closest causes maximum temperatures at the south poles to be higher than at the north poles. The minimum temperature on the Mars-facing hemispheres is higher than on the anti-Mars faces, due to thermal radiation from the Martian surface.

The temperature in the interior throughout history has also been modeled. The model was used to predict whether a conjectured icy component could have survived to the present. The conclusion was that primordial ice could still be present at depths of 10 m near the poles and 100 to 1000 m near the equator (Fanale and Salvail 1990).

Viking photography provides complete coverage of both bodies at a resolution of 200 m, and of some areas at a resolution of 10 m (Duxbury 1978). The shape of Phobos has been described in the form of a topographic map (Turner 1978), a sixth-order mathematical surface (Duxbury 1989), a globe (Turner 1978), and a computer model of radius versus latitude and longitude (Stooke 1989).

The surfaces of both moons are seen to be covered with a regolith of powdered rock. Regolith depth is difficult to estimate from photographs. Craters on Deimos seem to contain 6 to 12 m while craters on Phobos contain very little (Thomas and Veverka 1980). The regolith depth in valleys may be 200 m or more due to the downslope movement of surface deposits (Veverka and Thomas 1979).

Regolith particle size has been determined by two independent methods. The thermal inertia parameter of Phobos indicates "mean grain sizes tens to hundreds of micrometres" (Ksanfomality et al. 1989). Spectrally, bright material on Deimos matches C2 powder  $<40 \mu\text{m}$  in size, while dark material matches 75 to  $150 \mu\text{m}$  C2 powder (French et al. 1988).

Both moons exhibit many large (10 to 200 m) blocks on the surface, usually near large craters (Lee et al. 1986). Large blocks are especially

prominent near Stickney, the largest crater on Phobos. The degree to which the moons have been internally disrupted remains controversial.

A model of the interior of Phobos offers some insight into the relationship between external appearance and internal structure (Fujiwara and Asada 1983). Clay ellipsoids were fragmented by high-velocity projectiles to determine the effect of a near-catastrophic impact such as Stickney. The model was shattered and dispersed near the impact, and cracked into large chunks far from the impact. The resulting distribution of cracks is similar to the grooves observed on Phobos.

#### **D. Mining Economics**

Leonard et al. (1987) designed a commercial mining operation for producing water on Phobos or Deimos, for export to LEO. Their stated market was for propellant, needed to carry out the National Commission on Space scenario for a lunar base and a manned Mars mission. They proposed an automated mining, processing, and transport system for delivering water to LEO. The ice barges had a payload of 200 tons and a transit time of about 15 months. The ion rockets were powered by 10 MW electric plants. Their system cost estimate was \$1 billion to 5 billion.

### **VII. CONCLUSIONS**

The National Commission on Space (NCS) proposal for a manned lunar base and a manned exploration of Mars has created a context for the space program of the next century. If that proposal is implemented, the resources of near-Earth space could make the project much less expensive and much more self-sufficient. The timetable for designing an asteroid mine could probably match the NCS timetable.

The fundamental research and process development outlined in this review could be completed in about 6 yr. The prospecting spacecraft design and the asteroid selection could proceed in parallel with the research and development program. Allowing 1 yr for the prospecting mission, 5 yr for the pilot plant to be designed, tested and delivered, and 3 yr for the design and delivery of the scaled-up plant, the total time required comes to about 15 yr.

Recent history shows that few government programs survive that long. Thus, we might conclude that a substantial increase in long-term thinking is needed before space resources can play a leading role in public policy. Alternatively, the mining of asteroids could take the path of slow but steady progress, following rather than leading the breakout into space. While this author would prefer to see a National Asteroid Mining Initiative, he would gladly settle for a program based on sound economics. A reasonable precondition for building a \$3 billion asteroid mine is to have clear evidence of an economic advantage worth more than the cost. In space as on Earth, investments in infrastructure must somehow pay for themselves, whether they are publicly or privately funded.

Assuming that these preconditions can be met in the future, several near-term problems must be solved to keep the asteroid mining option open. Now that Spacewatch has broken the logjam of asteroid discovery, a new bottleneck has formed in the follow-up area. A list of 1000 new NEA discoveries is of no use if they are characterized only by orbital elements. High-quality spectral reflectance data on every NEA are most urgently needed.

The design of a plant for mining and processing asteroids presents a novel challenge. This may be the first design for which trial and error is completely unaffordable, and there is no established technology. Much development is needed in process simulation. This is an area with obvious spin-off potential. Every mining engineer would love to have a means of trying out a dozen variants on his process without bending any metal. Improved simulation requires improved models of mineralogy and better thermodynamic data. Once developed for asteroid mining, the rest of the world will benefit from it.

More experimental work is needed on processing of the asteroidal material we already have: meteorites. To date, nothing has been published on how carbonaceous material actually behaves in even the simplest proposed process. This is a fruitful area in economic terms. A small input of time and equipment can multiply our knowledge a hundred-fold.

Clever and adaptable robotics technology will be needed for the pilot plant. When it is needed, it probably will not be ready. This is a big future bottleneck waiting to happen.

Developing the new frontier in space will be slow, but it is guaranteed to be an exciting adventure. This is the first frontier in history which will be opened by engineers and scientists. It offers us an opportunity to learn to be responsible visionaries.

## REFERENCES

- Agosto, W. N. 1981. Beneficiation and powder metallurgical processing of lunar soil metal. In *Space Manufacturing 4, Proc. of the Fifth Princeton/AIAA Conf.*, eds. J. Grey and L. Hamdan (New York: AIAA), pp. 365–370.
- Allred, V. D. 1982. Oil shale retorting phenomenology. In *Oil Shale Processing Technology*, ed. V. Allred (East Brunswick, N. J.: The Center for Professional Advancement), pp. 55–66.
- Avanesov, G. A., Bonev, B. I., Kempe, F., Basilevsky, A., Boycheva, B., Chikov, K., Danz, M., Dmitrov, D., Duxbury, T., Gromatikov, P., Halmann, D., Head, J., Heifets, V., Kolov, V., Kostenko, V., Kottsov, V., Krasavtsev, V., Krasikov, V., Krumov, A., Kuzmin, A., Losev, K., Lumme, K., Mishev, D., Möhlmann, D., Muinonen, K., Muravev, V., Murchie, S., Murray, B., Neumann, W., Paul, L., Petkov, D., Petuchova, I., Pössel, W., Rebel, B., Shkuratov, Yu., Simeonov, S., Smith, B., Totev, A., Uzunov, Yu., Fedotov, V., Weide, G.-G., Zapfe, H., Zhukov,

- B., and Ziman, Ya. 1989. Television observations of Phobos: First results. *Nature* 341:585–587.
- Bibring, J.-P., Combes, M., Langevin, Y., Soufflot, A., Cara, C., Drossart, P., Encrenaz, Th., Erard, S., Forni, O., Gondet, B., Ksanfomalaly, L., Lellouch, E., Masson, Ph., Moroz, V., Rocard, F., Rosenqvist, J., and Sotin, C. 1989. Results from the ISM experiment. *Nature* 341:591–593.
- Bock, E. H., and Fisher, J. G. 1978. In-space propellant processing using water delivered as a shuttle contingency payload. Paper 78-941, presented at the 14th AIAA/SAE Joint Propulsion Conf., July 25–27.
- Bose, K., and Ganguly, J. 1991. Kinetics of volatile extraction from carbonaceous chondrites: Dehydration of talc. Resources of Near-Earth Space: Proc. Second Annual Symp. UA/NASA SERC, Jan. 7–10, Tucson, Ariz., Abstract book, p. 13.
- Britt, D., and Murchie, S. L. 1991. The composition of Phobos: Meteorite analogs based on KRFM and VSK spectral data from the Phobos 2 spacecraft. Resources of Near-Earth Space: Proc. Second Annual Symp. UA/NASA SERC, Jan. 7–10, Tucson, Ariz., Abstract book, p. 24.
- Burns, J. A. 1978. The dynamical evolution and origin of the martian moons. *Vistas in Astronomy* 22:193–210.
- Cordell, B., and Steinbronn, O. 1988. An analysis of possible advanced space strategies featuring the role of space resource utilization. Paper presented at the 39th Intl. Astronautical Congress. IAA-88-587.
- Cronin, J. R., Pizzarello, S., and Cruikshank, D. P. 1988. Organic matter in carbonaceous chondrites, planetary satellites, asteroids and comets. In *Meteorites and the Early Solar System*, eds. J. F. Kerridge and M. S. Matthews (Tucson: Univ. of Arizona Press), pp. 819–857.
- Cutler, A. H., and Hughes, M. L. 1985. Transportation economics of extraterrestrial resource utilization. In *Space Manufacturing 5: Engineering with Lunar and Asteroidal Materials*, eds. B. Faughnan and G. Maryniak (New York: AIAA), pp. 233–244.
- Davis, D. R., Housen, K. R., and Greenberg, R. 1981. The unusual dynamical environment of Phobos and Deimos. *Icarus* 47:220–233.
- Dobrovolskis, A. R., and Burns, J. A. 1980. Life near the Roche limit: Behavior of ejecta from satellites close to planets. *Icarus* 42:422–441.
- Duxbury, T. C. 1978. Spacecraft imaging of Phobos and Deimos. *Vistas in Astronomy* 22:149–161.
- Duxbury, T. C. 1989. The figure of Phobos. *Icarus* 78:169–180.
- Erstfeld, T. E., Mullins, O., Jr., and Williams, R. J. 1979. Carbon dioxide electrolysis using a ceramic electrolyte. In *Space Manufacturing Facilities 3*, eds. J. Grey and C. Krop (New York: AIAA), pp. 83–88.
- Fanale, F. P., and Salvail, J. R. 1990. Evolution of the water regime of Phobos. *Icarus* 88:380–395.
- French, J. R. 1989. Rocket propellants from Martian resources. *J. British Interplanet. Soc.* 42:167–170.
- French, L. M., Veverka, J., and Thomas, P. 1988. Brighter material on Deimos: A particle size effect in a carbonaceous material? *Icarus* 75:127–132.
- Fujiwara, A., and Asada, N. 1983. Impact fracture patterns on Phobos ellipsoids. *Icarus* 56:590–602.
- Funk, J. E. 1983. Coal technology. In *Riegel's Handbook of Industrial Chemistry*, ed. J. A. Kent (New York: Van Nostrand Reinhold), 8th ed., pp. 66–129.
- Gaffey, M. J., and McCord, T. B. 1979. Mineralogical and petrological characterizations of asteroid surface materials. In *Asteroids*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 688–723.
- Ganguly, J., and Saxena, S. K. 1989. Theoretical predictions of volatile bearing phases

- and volatile resources in some carbonaceous chondrites. In *Space Manufacturing 7: Space Resources to Improve Life on Earth*, eds. B. Faughnan and G. Maryniak (Washington, D. C.: AIAA), pp. 97–105.
- Garvey, J., and Magoffin, M. 1991. Lunar resource processing using solar energy: A research project status report. In *Space Manufacturing 8: Energy and Materials from Space*, eds. B. Faughnan and G. Maryniak (Washington, D. C.: AIAA), pp. 143–149.
- Gertsch, R. E., Barnes, R., Cutler, A. H., and Gaffey, M. 1985. Space resources. In *Proc. of the Fourth Annual L5 Space Development Conf.*, ed. F. Hecker, AAS 85–746 to 85–749 (San Diego: Univelt), pp. 63–90.
- Giese, B., and Kührt, E. 1990. Theoretical interpretation of infrared measurements at Deimos in the framework of crater radiation. *Icarus* 88:372–379.
- Gooding, J. L. 1975. A High-Temperature Study on the Vaporization of Alkalis from Molten Basalts Under High Vacuum: A Model for Lunar Volcanism. M. S. Thesis, Univ. of Hawaii.
- Gradie, J., and Tedesco, E. 1982. Compositional structure of the asteroid belt. *Science* 216:1405–1407.
- Grayson, M., and Eckroth, D., eds. 1982. Petroleum—survey of refinery process. In *Kirk-Othmer Encyclopedia of Chemical Technology*, vol. 17, 3rd ed. (New York: Wiley), p. 189.
- Grimm, R. E., and McSween, H. Y. 1989. Water and the thermal evolution of carbonaceous chondrite parent bodies. *Icarus* 82:244–280.
- Haberstroh, W. H., and Collins, D. E. 1983. Synthetic organic chemicals. In *Riegel's Handbook of Industrial Chemistry*, ed. J. A. Kent (New York: Van Nostrand Reinhold), 8th ed., pp. 66–129.
- Hartmann, W. K. 1987. A satellite-asteroid mystery and a possible early flux of scattered C-class asteroids. *Icarus* 71:57–68.
- Hartmann, W. K. 1990. Additional evidence about an early flux of C asteroids and the origin of Phobos. *Icarus* 87:236–240.
- Hashimoto, A., Kumazawa, M., and Onuma, N. 1979. Evaporative metamorphism of primitive dust material in the early solar nebula. *Earth Planet. Sci. Lett.* 43:13–21.
- Haskin, L., and Warren, P. 1991. Lunar chemistry. In *Lunar Sourcebook—A User's Guide to the Moon*, eds. G. H. Heiken, D. T. Vaniman and B. M. French (Cambridge: Cambridge Univ. Press), pp. 434–448.
- Hayes, J. M. 1967. Organic constituents of meteorites—A review. *Geochim. Cosmochim. Acta* 31:1395–1440.
- Heald, D. A., Blatt, M. H., Bock, E. H., Bradley, R. E., Drowns, R. E., and Leonard, K. E. 1978. Orbital Propellant Handling and Storage Systems for Large Space Programs. NASA Contractors Rept. JSC-13967 (Houston: Johnson Space Center).
- Heymann, D. 1971. The inert gases: He, Ne, Ar, Kr and Xe. In *Handbook of Elemental Abundances in Meteorites*, ed. B. Mason (New York: Gordon and Breach), pp. 29–44.
- Hodgson, G. W., and Baker, B. L. 1969. Porphyrins in meteorites: Metal complexes in Orgueil, Murray, Cold Bokkeveld, and Mokoia carbonaceous chondrites. *Geochim. Cosmochim. Acta* 33:943–958.
- Jones, T. D., Lebofsky, L. A., Lewis, J. S., and Marley, M. S. 1990. The composition and origin of the C, P, and D asteroids: Water as a tracer of thermal evolution in the outer belt. *Icarus* 88:172–192.
- Ksanfomality, L. V., Moroz, V. I., Bibring, J. P., Combes, M., Soufflot, A., Ganpantzerova, O. F., Goroshkova, N. V., Zharkov, A. V., Nikitin, G. E., and Petrova, E. V. 1989. Spatial variations in thermal and albedo properties of the surface of

- Phobos. *Nature* 341:588–591.
- Kührt, E., and Giese, B. 1989. A thermal model of the martian satellites. *Icarus* 81:102–112.
- Lebofsky, L., Jones, T. D., Owensby, P. D., Feierberg, M. A., and Consolmagno, G. J. 1990. The nature of low-albedo asteroids from 3- $\mu$ m multicolor photometry. *Icarus* 83:16–26.
- Lee, S. W., Thomas, P., and Veverka, J. 1986. Phobos, Deimos, and the moon: Size and distribution of crater ejecta. *Icarus* 68:77–86.
- Leonard, R. S., Blacic, J. D., and Vaniman, D. T. 1987. The economics of mining the Martian moons. In *Space Manufacturing 6: Nonterrestrial Resources, Biosciences, and Space Engineering*, eds. B. Faughnan and G. Maryniak (New York: AIAA), pp. 380–395.
- Levy, R. L., Wolf, C. J., Grayson, M., Gilbert, L., Updegrove, W. S., Zlatkis, A., and Oró, J. 1970. Organic analysis of the Pueblito de Allende meteorite. *Nature* 227:148–150.
- Lewis, J. S., and Nozette, S. 1983. Extraction and purification of iron-group and precious metals from asteroidal feedstocks. In *Space Manufacturing 1983*, eds. J. D. Burke and A. S. Whitt (San Diego: Univelt), pp. 351–353.
- Lewis, J. S., Jones, T. D., and Farrand, W. H. 1988. Carbonyl extraction of lunar and asteroidal metals. In *Engineering, Construction and Operations in Space*, eds. S. Johnson and J. Wetzel (New York: American Soc. of Civil Engineers), pp. 111–122.
- Lundin, R., Zakharov, A., Pellinen, R., Borg, H., Hultquist, B., Pissarenko, N., Dubinin, E. M., Barabash, S. W., Liede, I., and Koskinen, H. 1989. First measurements of the ionospheric plasma escape from Mars. *Nature* 341:609–612.
- Mason, B. 1966. The carbonaceous chondrites. *Space Science Rev.* 1:642.
- Meyer, T. R., and McKay, C. P. 1989. The resources of Mars for human settlement. *J. British Interplanet. Soc.* 42:147–160.
- Moore, C. B. 1971. Nitrogen. In *Handbook of Elemental Abundances in Meteorites*, ed. B. Mason (New York: Gordon and Breach), p. 96.
- Mul, J. M., Korting, P. A. O. G., and Schoyer, H. F. R. 1990. A search for new storable high-performance propellants. *ESA Journal* 14:253–270.
- Neary, R. M. 1983. Industrial gases. In *Riegel's Handbook of Industrial Chemistry*, ed. J. A. Kent (New York: Van Nostrand Reinhold), 8th ed., pp. 607–630.
- Ness, R. O., Jr., Sharp, L. L., Runge, B. D., Knudsen, C. W., and Gibson, M. A. 1991. Hydrogen reduction of lunar simulants for the production of oxygen in a continuous fluid-bed reactor. In *Space Manufacturing 8: Energy and Materials from Space*, eds. B. Faughnan and G. Maryniak (Washington, D. C.: AIAA), pp. 325–330.
- O'Leary, B. 1985. Phobos and Deimos (PhD): Concept for an early human mission for resources and science. In *Space Manufacturing 5: Engineering with Lunar and Asteroidal Materials*, ed. B. Faughnan and G. Maryniak (New York: AIAA), pp. 41–48.
- Pang, K. D., Pollack, J. B., Veverka, J., Lane, A. L., and Ajello, J. M. 1978. The composition of Phobos: Evidence for carbonaceous chondrite surface from spectral analysis. *Science* 199:64–66.
- Perry, R. H., and Chilton, C. H. 1973. *Chemical Engineers' Handbook*, 5th ed. (New York: McGraw-Hill), pp. 8–11.
- Pollack, J. B., Veverka, J., Pang, K., Colburn, D., Lane, A. L., and Ajello, J. M. 1978. Multicolor observations of Phobos with the Viking lander cameras: Evidence for a carbonaceous chondritic composition. *Science* 199:66–69.
- Reed, G. W., Jr. 1971. Fluorine and chlorine. In *Handbook of Elemental Abundances in Meteorites*, ed. B. Mason (New York: Gordon and Breach), pp. 103–106;



- 143–147.
- Rosenbauer, H., Shutte, N., Apathy, I., Galeev, A., Gringauz, K., Grunwaldt, H., Hemmerich, P., Jockers, K., Kiraly, P., Kurova, G., Livi, S., Marsch, E., Richter, A., Riedler, W., Remizov, T., Schwenn, R., Schwingenschuh, K., Steller, M., Szego, K., Verigin, M., and Witte, M. 1989. Ions of martian origin and plasma sheet in the martian magnetosphere: Initial results of the TAUS experiment. *Nature* 341:612–614.
- Rosenberg, S., Guter, G., and Miller, F. 1965. Manufacture of oxygen from lunar materials. *Annals of the New York Academy of Science* 123:1106–1122.
- Schuster, J. R., Bennett, F. O., Alton, T. J., Johns, W. A., Kim, I., Liggett, M. W., Simon, M. C., and Torre, C. N. 1986. Long Term Cryogenic Storage Facility Systems Study, Interim Report, Part A: Executive Summary. NASA GDSSD-SP-86-038, prepared for Marshall Space Flight Center by General Dynamics Space Systems Division, San Diego, Ca.
- Shoemaker, E. M., Williams, J. G., Helin, E. F., and Wolfe, R. F. 1979. Earthcrossing asteroids: Orbital classes, collision rates with Earth, and origin. In *Asteroids*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 783–806.
- Simoneit, B. R., Christiansen, P. C., and Burlingame, A. L. 1973. Volatile element chemistry of selected lunar, meteoritic, and terrestrial samples. *Proc. Lunar Sci. Conf. 4, Geochim. Cosmochim. Acta Suppl. 2*:1635–1650.
- Smith, J. W., and Jensen, H. B. 1987. Oil shale. In *Encyclopedia of Science and Technology*, 6th ed. (New York: McGraw-Hill) 12:333–340.
- Smoot, L. D. 1979. General characteristics of coal. In *Pulverized-Coal Combustion and Gasification*, eds. L. Smoot and D. Pratt (New York: Plenum Press), pp. 123–132.
- Stooke, P. J. 1989. Sizing up Phobos. *Sky & Telescope* 1989:477.
- Studier, M. H., Hayatsu, R., and Anders, E. 1972. Origin of organic matter in the early solar system: V. Further studies of meteoritic hydrocarbons and a discussion of their origin. *Geochim. Cosmochim. Acta* 36:189–215.
- Tholen, D. J., and Barucci, M. A. 1989. Asteroid taxonomy. In *Asteroids II*, eds. R. P. Binzel, T. Gehrels and M. S. Matthews (Tucson: Univ. of Arizona Press), pp. 298–315.
- Thomas, P., and Veverka, J. 1980. Downslope movement of material on Deimos. *Icarus* 42:234–250.
- Thomas, P., Veverka, J., and Dermott, S. 1986. Small satellites. In *Satellites*, ed. J. A. Burns (Tucson: Univ. of Arizona Press), pp. 802–835.
- Turner, R. 1978. A model of Phobos. *Icarus* 33:116–140.
- Veverka, J. 1978. The surfaces of Phobos and Deimos. *Vistas in Astronomy* 22:163–192.
- Veverka, J., and Thomas, P. 1979. Phobos and Deimos: A preview of what asteroids are like? In *Asteroids*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 628–645.
- Weast, R., ed. 1983. In *Handbook of Chemistry and Physics*, 64th ed. (Boca Raton, Fl.: CRC Press), pp. B:65–158, C:65–576.
- Weiblen, P. W., Murawa, M. J., and Reid, K. J. 1990. Preparation of simulants for lunar surface materials. In *Engineering, Construction, and Operations in Space II: Proc. of Space 90*, vol. 1, eds. S. Johnson and J. Wetzel (New York: American Soc. of Civil Engineers), pp. 98–106.
- Windholz, M., ed. 1983. In *The Merck Index*, 10th ed. (Rahway, N. J.: Merck & Co.); see alphabetical listings.
- Wszolek, P. C., Simoneit, B. R., and Burlingame, A. L. 1973. Studies of magnetic fines and volatile-rich soils: Possible meteoritic and volcanic contributions to lunar carbon and light element chemistry. In *Proc. Lunar Sci. Conf. 4, Geochim.*

- Cosmochim. Acta Suppl.* 2:1693–1706.
- Zellner, B. 1979. Asteroid taxonomy and the distribution of the compositional types. In *Asteroids*, ed. T. Gehrels (Tucson: Univ. of Arizona Press), pp. 783–806.
- Zhao, Y., and Shadman, F. 1991. Reaction engineering for materials processing in space: Reduction of ilmenite by hydrogen and carbon monoxide. Resources of Near-Earth Space: Proc. Second Annual Symp. UA/NASA SERC, Jan. 7–10, Tucson, Ariz., Abstract book, p. 12.
- Zinner, E. 1988. Interstellar cloud material in meteorites. In *Meteorites and the Early Solar System*, eds. J. F. Kerridge and M. S. Matthews (Tucson: Univ. of Arizona Press), pp. 956–983.