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ASTEROIDS: A SOURCE OF NATURAL RESOURCES FOR TERRESTRIAL AND EXTRA-TERRESTRIAL APPLICATIONS.

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The visible and near infrared (0.32-1.6μm) reflectance spectra of about 100 asteroids are available in the literature (1). These spectra can be interpreted utilizing diognostic mineral absorption features and spectral parameters to determine the mineralogy and petrology of their surface materials (2). Assemblages of minerals typically found in meteorites (Ni-Fe, pyroxene, olivine, feldspar, carbonaceous materials) dominate as asteroid surface materials. The surfaces of Asteroid Belt bodies (≃2.2-3.6AU) are primarily materials similar to carbonaceous chondrites and iron and stony-iron meteorites. The Apollo and Amor (perihelion < 1.0 and 1.5 AU respectively) seem to be of ordinary chondritic materials (Px,Ol,Ni-Fe,Fd) (3). The abundance of native metal phases in the surface materials of these objects raised the obvious question of the feasibility of acquisition and utilization of these materials either in space or on the Earth. We have completed a preliminary qualitative and quantitative investigation of this concept. We have evaluated in at least a general way, the physical, social and economic problems and/or benefits resulting from such access to extra-terrestrial sources of the Ni-Fe metals.

In terms of supplying materials for large-scale operations in near-earth space, asteroidal sources appear to be competitive with lunar or terrestrial sources. The direct energy requirement for delivering materials to near-earth space (eg. 5-60 Earth radii) are: Earth's surface ≃ 40-65 x 10^6 joules/kg; Lunar surface ≃ 3-15 x 10^6 joules/kg; Belt asteroids ≃ 30-80 x 10^6 joules/kg and Apollo and Amor asteroids ≃ 3-100 x 10^6 joules/kg. It is probable that some or all of the Apollo group objects are extinct cometary nuclei and thus should contain the volatile hydrogen, carbon and nitrogen phases beneath a layer of insulating overburden (4). Since these vital materials are rare or absent on the lunar surface, the Apollo objects provide a significantly cheaper alternative than a terrestrial source.

The main thrust of our effort has been concerned with acquisition and delivery of the Ni-Fe group metals to the Earth's surface for terrestrial applications. There appears to be strong economic and environmental incentives to undertake such a program. Utilizing realistic and conservative assumptions concerning terrestrial demand, prices and delivery rates for these metals at some point in the relatively near future (eg. 30 to 40 years), it should be possible to realize an annual gross return of $100-200 billion (in 1975 dollars), for an investment comparable to the presently projected capitalization program of the Western iron industry over the same interval. The direct energy cost of producing raw iron from high-grade iron ore (iron oxide) is about 17 x 10^6 joules/kg and will continue to increase as the grade of terrestrial ores and fuel sources continue to decrease. Thus even at the present time, certain asteroidal bodies could supply iron to the Earth's surface at a lower energy cost than terrestrial sources, and this balance will shift more strongly in favor of the asteroidal sources in the future. In addition, the increasing terrestrial dependence on lower and lower grade ores will result in an increased environmental impact as more raw ore and fuel must be mined, more terrain disrupted and more waste products disposed of to obtain the same amount of metal (5). Access to extra-terrestrial sources of these metals would remove this environmental damage and the decline in quality of life and/or increase in cost of materials which results. In effect, the mines and factories no longer need be anybodys backyard. This proposal should not be viewed as displacing the terrestrial iron industry and its' labor pool, since the decline in grade of ore will require an increase per unit of metal in both the plant and labor required for terrestrial processing.

Technically, the proposal appears to be quite feasible as outlined in the following scenario. The Ni-Fe metal is brought into near-earth space either by moving a small asteroid ($\simeq$ 1 km) by means of nuclear pulse propulsion (6) on a near-term basis or from an independent, self-sufficient mining colony situated on an appropriate asteroid on a longer-term basis. In a large factory/colony near 60 Earth radii, the metal is melted and refined in solar furnaces, a volatile phase injected into the melt to produce a metal foam ($\rho \simeq 0.5$ gm/cm^3) and fabricated into a large-scale (10,000 to 100,000 tons) lifting-body with a low mass/cross-section ratio (100 to 1000 gm/cm^2). The orbit of this body is perturbed to arrange a close encounter with the Moon and thus convert an essentially circular geocentric orbit into an extremely eccentric orbit with perigee near the Earth's surface. (Such gravitational modification of orbital parameters requires precision guidence but little direct energy input.) After the Lunar encounter, the orbit is refined to achieve a tangetial atmospheric graze at about 80 kilometers altitude with a lift/drag ratio of 0.1 to 1.0. Such conditions permit the atmospheric entry and decleration of the body without the surface of the body reaching the melting point of Ni-Fe metal, so that ablation is minimal and no problem of particulate pollution of the upper atmosphere is introduced. The low density of the body permits landing to take place in the oceans where it will float for subsequant recovery. Terminal velocity in the lower atmosphere is approximately 60 meters per second so that no large impacts will occur.

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DISCUSSION (Gaffey and McCord Paper)

SPEAKER 1: One now uses spectrophotometry and similar astronomical methods to infer the surface composition of observed asteroids. I'd like to ask this. Can we look at a specific asteroid, such as Vesta or 1976 AA or what will, and in the surface spectra see actual evidence for native metals, for reduced metals or is it simply by analogy with meteoroids that you are arguing that these metals exist?

GAFFEY: We can look at any asteroid that's bright enough - and if you look at Vesta you aren't going to see any metal because there isn't any metal there. Vesta is a very nice spectrum and indeed it's a nice clean silicate that's rather well characterized at this point in time. A lot of work has been done. You can look at a fairly large number of objects; roughly a third of all of the asteroids we looked at appear to have surface compositions ranging from 25 to 100 percent metallic nickel-iron.

SPEAKER 1: On what do you base that?

GAFFEY: On the behavior of the spectral characteristics. Nickel-iron has a characteristic spectral signature.

SPEAKER 1: So then you actually do see a signature of nickel-iron in some asteroids. Could you name a few asteroids which show very high abundnace?

GAFFEY: Three Juno, 15 Eunomia, 39 Lutetia, 40 Harmonia, 354 Elinora -- how far do you want me to go up in numbers?

SPEAKER 2: What about evidence for water ices or asteroids that might have a lot of water content to them? Can you tell that from ground-based observations?

GAFFEY: You won't see any stable water ices in the inner solar system because literally they're not stable. Inside the orbit of Jupiter, ices exposed to the solar radiation do not last for reasonably long periods of time. What you do see is objects, for example - I can't pronounce the name, it's Indian I believe it is, which was originally identified as a comet; it had a transient feature. Penogium, I believe, is the name. In subsequent passes, it is classified as an asteroid. It shows no transient phenomena. This is direct evidence that that object has volatile phases buried in the surface. The other example is things of carbonaceous chondritic composition range in the low metamorphic grades from 20 percent water, bound water, down to in the high grades 1 or 2 percent bound water. In this case we see a large number of low-grade carbonaceous chondritic material. We do not see the water directly; we see the assemblage that's tied up.