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PART 3—Manufacturing and Fabrication

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Introduction

The ability to use nonterrestrial materials and energy and to utilize the special properties of space environments will allow the space enterprise to grow at an increased rate. We can envision a self-sufficient space economy, with centers of resource extraction and manufacturing off Earth that provide sustenance to colonies of people. However, in the next 25 years, the infrastructure for using space resources will concentrate on more limited goals, those that will have high leverage on the space economy.

Four general goals for use of nonterrestrial resources are

1. To decrease the cost of transporting various systems beyond low Earth orbit (LEO) by providing propellant or reaction mass at a reduced cost
2. To reduce or eliminate the transportation costs for systems emplaced on other planetary surfaces and in space by using indigenous materials
3. To increase supplies of energy to Earth orbit and the Earth
4. To provide previously unattainable products by utilizing the special materials and unique processing capabilities afforded by space environments

Several possibilities exist to make major augmentations to our space capability by providing access to materials in space:

1. Provision of liquid oxygen can significantly reduce the need to transport propellant from Earth to low Earth orbit and reduce the cost of transportation to and from a lunar base.
2. Provision of material can decrease the costs of insulation and of shielding against radiation and impact for satellites in Earth orbit and human habitats beyond low Earth orbit.
3. Structural material, including pressurizable volumes, could be provided for Earth orbit or lunar bases.
4. Byproducts from nonterrestrial processing systems could begin to make living in space easier.

5. Energy collected in space could be used directly or by conversion to electricity to carry out space manufacturing enterprises.

6. Space debris could be recovered and reused or put to a new use.

This report is deliberately conservative. Previous studies (Criswell 1980) have demonstrated that nearly anything one wants to make in space can be made from the raw materials available on the Moon or on near-Earth asteroids. We have looked instead at what is most easily accomplished in the next 25 years.

The accessibility of material and energy off the Earth and the leverage that these nonterrestrial resources can exert on the space transportation system are important influences on the long-term goal of exploring the solar system. The next 25 years will provide the learning experience necessary to advance that activity more rapidly. The concept of "bootstrapping"—using the production capability to manufacture additional production equipment and expand production more rapidly than if all the production equipment had to be transported from Earth—can be tested and the ability to sustain human settlement beyond Earth can be demonstrated.

Research on separation of lunar materials and manufacture of useful products from them is in its infancy. Many avenues are left to be investigated. A few possible processes and products are described below.

Products

The least complicated technologies will not necessarily be the most cost-effective ones to manufacture products from nonterrestrial materials. It is nevertheless appealing to imagine that early space manufacture can be done by simple means. It seems that simplicity ought to correlate with economy or at least with probability of early application. Thus, we have chosen to explore the oxygen, metal, and silicate products that might be obtained from simple treatment of well-characterized materials from near-Earth space.

The ground rules of the exercise are these:

1. Starting materials are those substances found in greatest abundance at the lunar sites visited by the Apollo astronauts. More exotic lunar ores and water at the poles are excluded from consideration. So are all asteroidal materials, their exact nature being still unknown.

2. Raw materials for manufacture are materials in "as found" condition or materials upgraded or separated by only the simplest means.

3. Products are for use on the Moon or in orbit, not on Earth.

4. The additives, catalysts, and processing materials that must be supplied from Earth will be kept to a minimum.

5. Oxygen, perhaps extracted from ilmenite-rich material, will be an important early lunar product.

6. Materials used in space applications will be those available and adequate, not necessarily those traditionally envisioned or preferred.

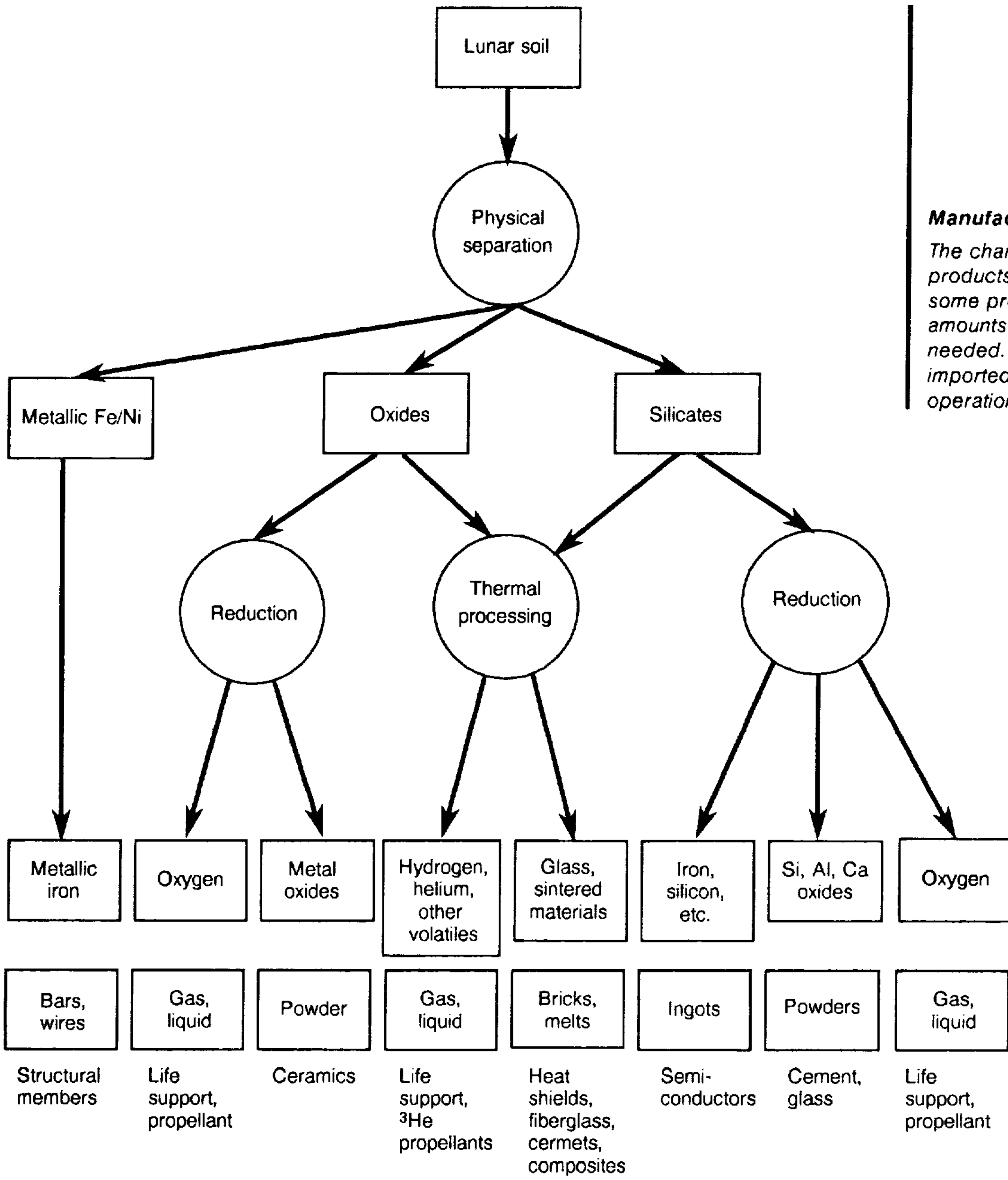
7. The quality of material used may not match that of similar material produced on Earth, and sizes and quantities will be adjusted accordingly.

8. The complex components that are necessary will be imported from Earth.

9. Steps in manufacture must be few, easy, and reliable.

10. Assembly and application of products must be simple and rapid and tolerances relatively loose.

11. All processes up through assembly should be reasonably automated but tended. Equipment should be easy for its operators to repair, optimize to actual conditions, and adapt to new feedstocks and applications.



Manufacturing on the Moon

The chart shows various sources and products utilizing lunar materials. For some products with special uses, small amounts of material from Earth may be needed. Conservation and recycling of imported materials will be important in operational systems, such as life support.

The scenario that could result from application of these ground rules to common materials at Apollo sites is limited but far from stifling. To make the problem tractable for this exercise, we have chosen to constrain our list of materials and products even more narrowly than the rules specify. Nevertheless, the examples we treat should be sufficient to illustrate the possibilities and the limitations.

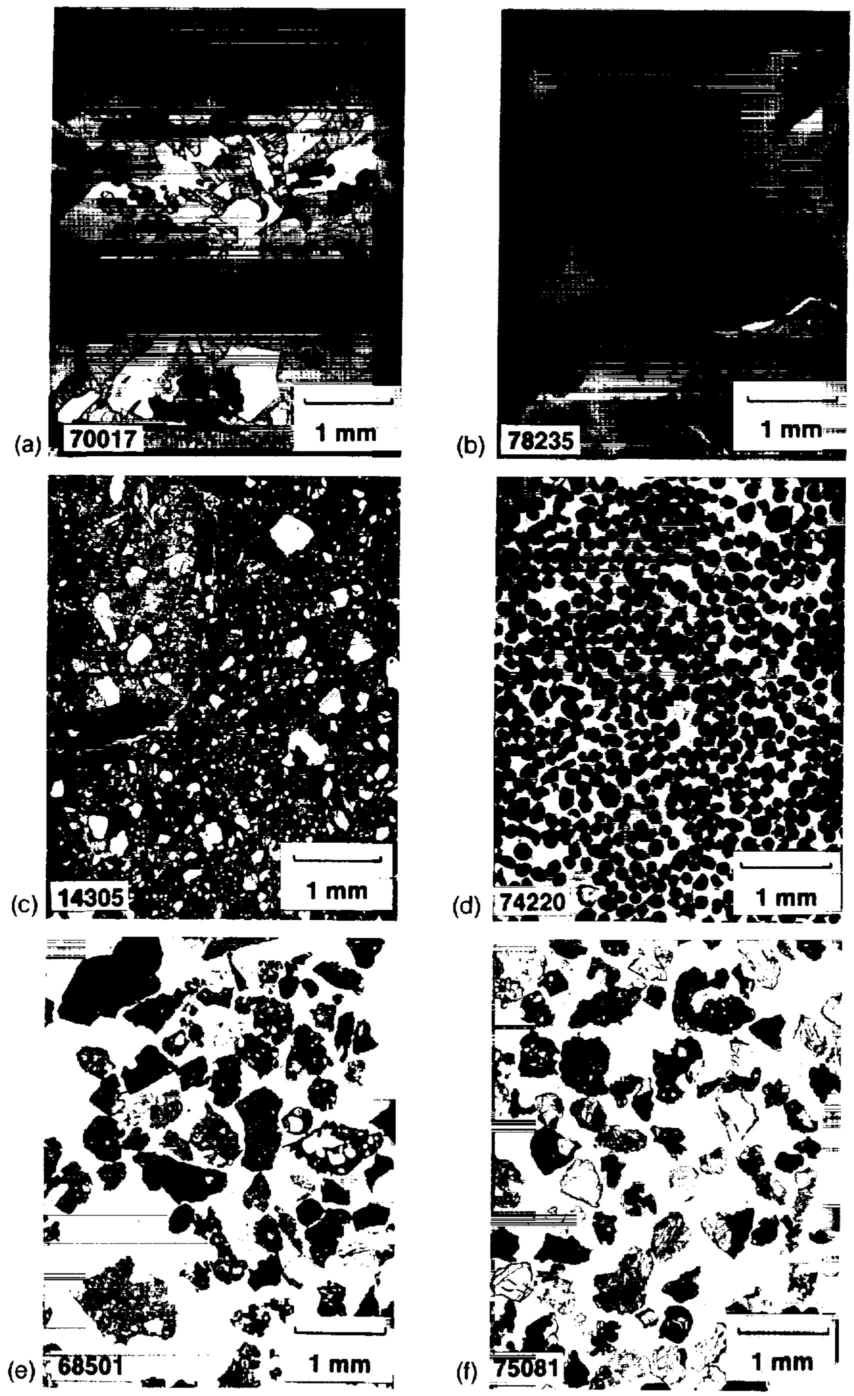
The following are designated as starting materials:

I. Unprocessed lunar regolith

- A. Bulk soil
  1. Mare-derived; high-iron, high-silicon, low-aluminum, low-calcium
  2. Highland-derived; low-iron, high-silicon, high-aluminum, low-calcium
  3. Mixed origin; intermediate-composition
- B. Rocks
  1. Mare basalt [$CaAl_2Si_2O_8$ (plagioclase) and $(Mg,Fe)SiO_3$ (low-calcium pyroxene)]
  2. Highland igneous rocks
     - a. Anorthite (primarily plagioclase)
     - b. Dunite [primarily $(Mg,Fe)_2SiO_4$ (olivine)]
     - c. Troctolite (mixtures of plagioclase and olivine)
     - d. Norite (mixtures of plagioclase and low-calcium pyroxene)
  3. Breccias (physical mixtures of rock, mineral, and glass fragments)

II. Minimally processed regolith (no chemical extraction)

- A. Magnetic iron-nickel alloys plus iron-bearing glassy "agglutinates" (separated magnetically)
- B. Ilmenite concentrate, $FeTiO_3$ (separated electrostatically)
- C. Plagioclase concentrate (separated paramagnetically or electrostatically)
- D. Residues from separations of A through C
- E. Volatiles (H_2, N_2, He) driven off thermally



Intermediate Products

Lunar rocks and the regolith consist of minerals and glasses, which can be separated by several means. Here, a variety of lunar materials are shown as they appear in very thin slices viewed with a microscope in transmitted light.

a. Basalt, consisting of intergrown crystals of plagioclase feldspar (clear), olivine and pyroxene (dark, transparent), and ilmenite (black, opaque).

b. Norite, consisting primarily of plagioclase feldspar and low-calcium pyroxene, in coarse grains.

c. Breccia, showing very fine-grained material enclosing larger rock fragments.

d. Orange soil. This is a peculiar soil consisting primarily of beads of orange glass of basaltic composition, probably formed in a volcanic fire fountain.

e. Fragments from typical highland regolith. Agglutinates are fused regolith material, which formed tiny gas bubbles as they melted and were quenched.

f. Typical millimeter-size fragments in mare regolith. At millimeter sizes, most lunar regolith grains are complex, consisting of more than one mineral. At smaller sizes, a higher fraction of the grains consist of only a single mineral.

Mineral separation (beneficiation) techniques utilize the different properties of the minerals and glasses to separate them. The techniques include size, magnetic, specific gravity, and electrostatic separation. Mixed grains are more difficult to separate by physical means.

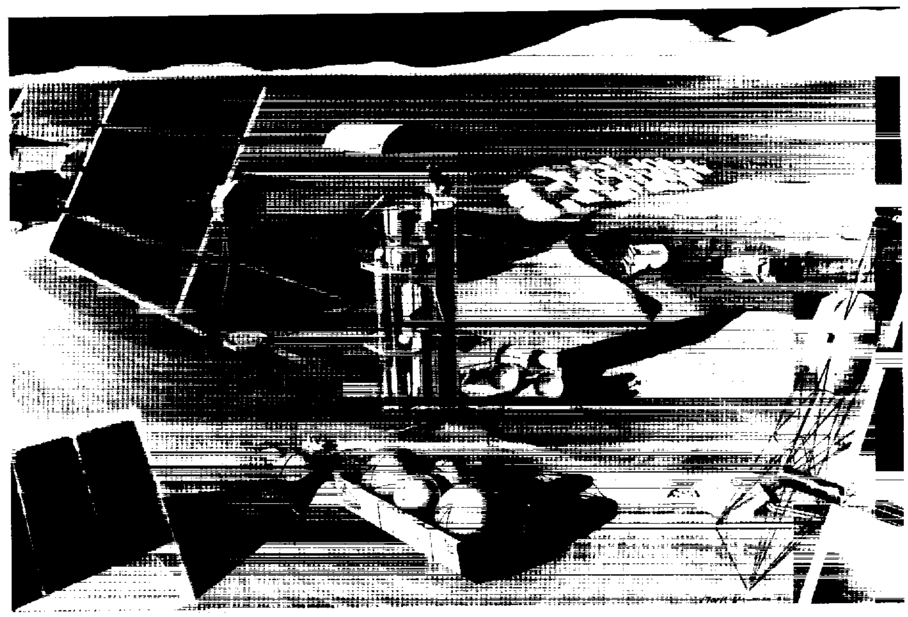
Chemical Processes

a. Ilmenite Reduction

A facility such as this could use hydrogen to chemically reduce ilmenite ($FeTiO_3$), thus producing iron metal, titanium dioxide, and water. The water is then electrolyzed, to split the hydrogen and oxygen. The hydrogen is recycled to the reduction process, and the oxygen is liquefied and stored for use. The oxygen has use in the transportation system as propellant, in life support systems, and in other chemical processing, thereby offsetting the need to import it from Earth.

The residue from the process may have uses as well. It typically would consist of an intimate mixture of iron (alloyed with small amounts of silicon and titanium) and titanium dioxide (rutile). The metal can be separated either by melting or by a chemical process (e.g., carbonyl processing). The titanium dioxide may find use as a ceramic material. The combined slag from the process may find use as a structural material through allowing it to sinter (compact and harden) while it cools from high temperature.

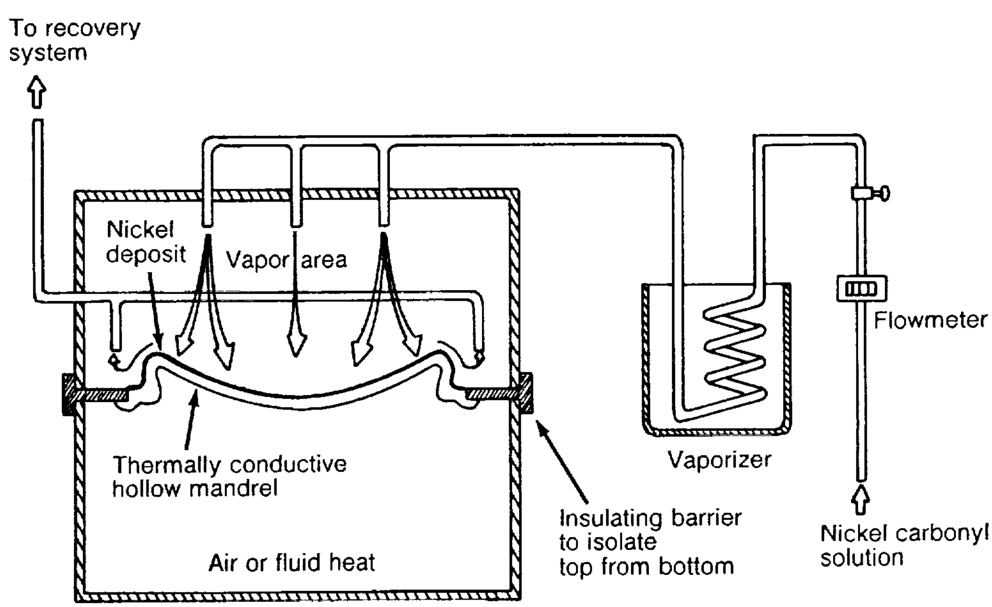
Artist: Mark Dowman

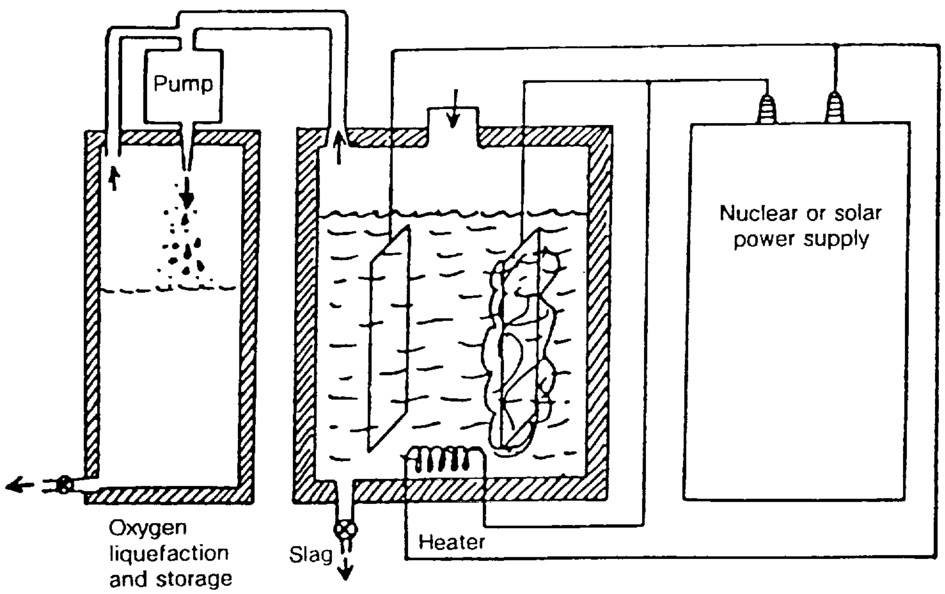


b. Carbonyl Processing

Carbonyl processing (the Mond process) is a well-known procedure for extracting nickel from metal by reaction with carbon monoxide gas. The metals in the residue from the hydrogen reduction of ilmenite could be separated from one another and from the rutile by the carbonyl process. Or the process could be applied to meteorites found in the lunar regolith to separate the nickel and iron in them. In addition, as depicted in the illustration, the gaseous carbonyl can be used to directly deposit metal coatings or even metal objects.

Courtesy of Vaporform Products; taken from Meinel 1985, p. 157.





Magma electrolysis cell

c. Electrolysis

Silicate electrolysis is similar in concept to the simple electrolysis cell used to dissociate water into hydrogen and oxygen. Instead of water, molten silicate forms the solution which conducts electrons from the cathode to the anode. As those electrons are transferred, the iron in the silicate is reduced to metal and oxygen is released. Recent studies (Lindstrom and Haskin 1979) have shown that some titanium and silicon can also be reduced to metal in this manner. The electrodes are the critical element of the electrolysis cell. If they become corroded or damaged, the cell will cease to function. If the rate of deterioration is high and new electrodes need to be brought from Earth regularly, part of the benefit of using the indigenous materials is lost.

From Lewis, Jones, and Farrand 1988, p. 116.

d. Solar Furnace

It is possible to separate some elements from molten materials simply on the basis of their volatility. Solar concentrators, such as this one in Odeillo, France, can achieve temperatures higher than 3500°C. If typical lunar rocks are heated to the vicinity of 2000°C, first sodium and potassium evaporate, then silicon and iron, leaving primarily a mixture of calcium, aluminum, magnesium, and titanium. Some reduction to metal may occur. The resulting residue may be quite similar to compounds used in Portland cements on Earth.

Photo: Elbert A. King

III. Maximally processed regolith (chemical extraction)

A. Elemental oxygen (product of reduction of lunar material)

B. Residues from oxygen smelting (e.g., from the ilmenite reduction process): rutile (TiO_2), elemental iron, silicate impurities, all intimately mixed

C. Products from carbonyl processing of metal concentrates
1. High purity iron metal
2. High purity nickel metal
3. Rutile plus silicate impurities

D. Products of electrolysis of basalt
1. Iron metal, with perhaps up to 2 percent manganese and chromium
2. Iron metal with several percent titanium
3. Iron metal with several percent silicon

E. Products from solar furnace evaporation of silicates
1. Calcium aluminate cement
2. Metals, including iron and silicon

Indigenous conditions assumed are vacuum, sunlight, low gravity on the Moon, and microgravity in near-Earth space. Tools and facilities that should be available include solar furnaces and electrical power at megawatt levels.

From this set of starting materials and facilities, the following classes of products are possible. These are evaluated with respect to properties attainable without further change or purification. Additional equipment needed to produce the products from the starting materials is identified. Also, additives that in small quantities could greatly improve the caliber of these products are identified. Gases, such as oxygen, hydrogen, carbon dioxide, and helium, are useful as generated and do not require further processing.

I. Metal-based

   A. Extruded products—beams, rods, wires

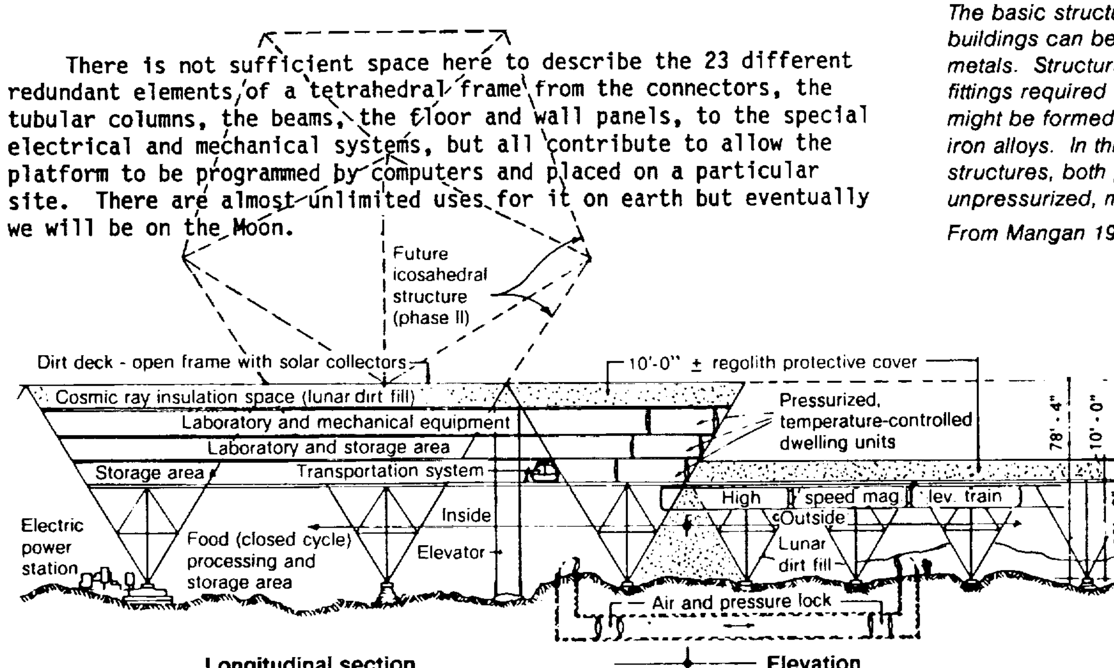
   B. Cast products—beams, rods, containers

   C. Rolled parts—plates, foils, beams

Structural Framework

The basic structural framework for buildings can be produced from lunar metals. Structural members and the fittings required to join them together might be formed by extruding lunar iron or iron alloys. In this manner, extensive structures, both pressurized and unpressurized, might be built.

From Mangan 1988, p. 380.



The Expandable Platform on the Moon

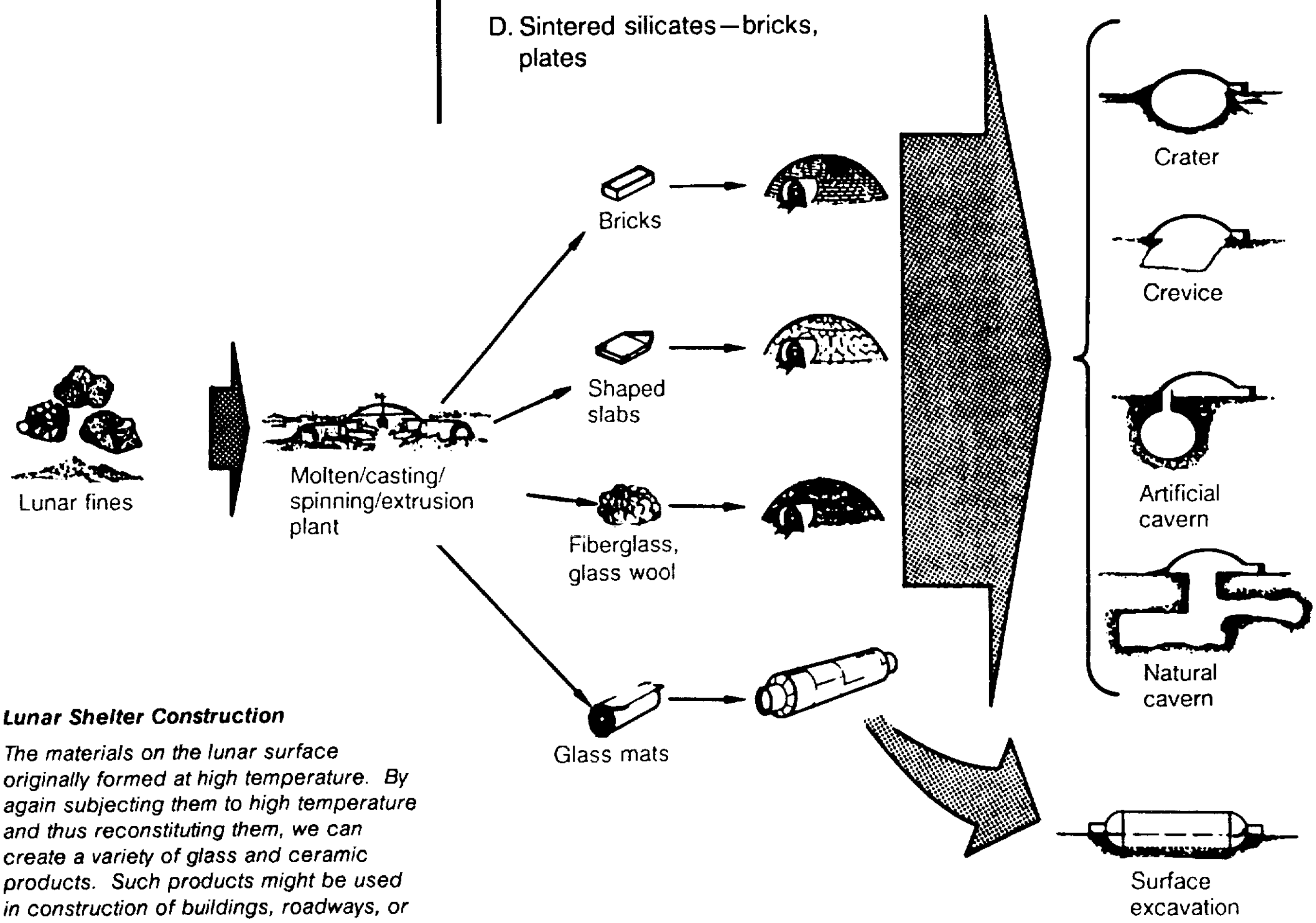
II. Silicate-based

A. Glasses—fibers, rods, light pipes, beams, bricks, coatings, sheets

B. Ceramics, cermets*—containers, bricks, pipes

C. Composites—cement, concrete

D. Sintered silicates—bricks, plates



Lunar Shelter Construction

The materials on the lunar surface originally formed at high temperature. By again subjecting them to high temperature and thus reconstituting them, we can create a variety of glass and ceramic products. Such products might be used in construction of buildings, roadways, or rocket landing pads. Construction materials derived from lunar regolith could be used in combination with excavations of the subsurface to expand habitable volume.

*A *cermet* [cer amic + *met* al] is a strong alloy of a heat-resistant compound (as titanium carbide) and a metal (as nickel) used especially for turbine blades. Also called a *ceramal*.