NON-TERRESTRIAL MATERIALS (NTM's) UTILIZATION David R. Criswell
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The many 1959-80 space accomplishments have been embodied in an average mass flow off-earth of approximately 40kg/hr (propellant) and 20kg/hr (hardware). Space shuttle transport into LEO will likely be less in the 1980's. There is a growing conviction by some researchers that far higher rates of introduction of useful (and more flexible) mass off-earth can be obtained by sending systems of production (machines and people) to other solar system objects. Facilities and products would be made predominately from local resources. In this manner limitations of the rocket equation, terrestrial funding restrictions and capabilities preconceptions could be attenuated. Growing resources and facilities could be created off-earth.

A vigorous Appolo program of lunar utilization was precluded in 1964 by decisions of the Johnson Administration to not pursue an extensive Apollo Applications program in which larger Apollo style missions would be mounted for the moon and possibly Mars (1). Lack of 1970-80's inexpensive microcomputers and the associated experience and philosophy of industrial production using machine-monitored systems certainly must have contributed to 1960's opinions that space exploitation would require enormous resources on earth for any use of NTM's. Lack of detailed knowledge of future space operations capabilities, costs, and of the materials to used also forced early concepts of utilization to be general and often focused on inappropriate topics (2). However, detailed examinations of the returned lunar samples now allow much more precise selections of lunar options (3.4). Rapidly increasing knowledge of the asteroids and their relation to meteorites examined on earth permit some delimiting of the options for the use of asteroids (5). Additional motivations arose from investigations of the construction of habitats in space (6) and by the arguments (7) that lunar resources could be used to achieve more economical and larger scale production of solar power stations in space (8) to provide power on earth.

In 1975 an ASEE/NASA (9) summer study examined the use of lunar materials in the construction of a permanent (10 million ton) human habitat to be located in cis-lunar space. It was concluded that a large fraction of the materials could be obtained from the moon and that much of the technology for such an undertaking was definable. The 1976 study (10) focused on-ejection of materials off the moon by electromagnetic mass drivers with power provided by solar energy; a survey of lunar raw materials and general examination of their use in glass/ceramic products and a scheme (subsequently found unsatisfactory; see 12) for the thermochemical processing of lunar soil; and a survey of the design features of a space manufacturing facility which utilized many parallel production units each of which could be manufactured in part from lunar materials.

The 1977 study (11) was of a larger scale (40 full time professional researchers and 20 NASA participants). Five major themes were examined: life support systems (regenerative); habitat designs; mass drive; asteroid resources; and NTM processing. The major aspects were analyzed for obtaining 240,000 tons/year of materials from the moon for the construction in space of a facility (3,000 people) to manufacture 2.4 SPS/year each with 10 Gigawatts of capacity. This study is especially significant as a baseline. It assists in understanding alternative approaches, uncovered many research needs and was used to define three subsequent detailed studies.

Extensive analysis of the primary materials processing procedures of excavation, beneficiation, glass/ceramic production and chemical process-

ing by means of solvent systems utilizing recycled process chemicals have revealed that much terrestrial technology can be applied to the creation of growing industries on the moon or in space (12). Extensive but precise research needs were listed for the further development of terrestrial technologies applicable to NTM's. Many concepts for processing specialized to the lunar environment were proposed (ex-enhancing trace elements in melt ponds by controlled devitrification).

Mass. Inst. of Tech. (13) conducted design studies of the manufacture in space of SPS from non-terrestrial feedstocks. The space manufacturing facility (SMF) was found to be technically feasible, capable of versatile and flexible production, offered production advantages (ex-direct vapor deposition of solar cells and other complex patterns) and considered to offer economic advantages (compared to earth production) by permitting SPS designs optimized for space condition. General Dynamics (14) conducted an extensive systems analysis of the construction of one 10 Gigawatt SPS/year over a 30 year period by means of 128,000 tons of facilities deployed completely from earth in 3 years. Approximately 90% of the SPS construction materials were to be obtained from the moon. Under these ground rules it was concluded that a massive product, such as SPS, would be required to justify NTM use; significant economic benefits derived by NTM use due to lower transportation costs and by space manufacturing; NTM based production of SPS was highly probable to be more attractive than deployment of systems from earth after 30 units (possibly competitive from the first unit). The rapid deployment of massive facilities from earth required the creation of a facilities and launch vehicles development effort almost as large as envisioned for deployment of SPS from earth. The semi-annual Princeton conferences on space manufacturing provide documentation of the evolution of these concepts (15).

Massive (150-300B$) investments over 10 to 30 year time scales for the deployment of major manufacturing facilities on the moon and in space encouraged exploration of alternative approaches. One approach is to make use of parallelism in production. Construct the smallest reasonable sizes of initial lunar bases and initial construction facilities in space. Then concentrate the initial productive output on the rapid growth of lunar/space facilities. One study (16) indicated that a 40 ton lunar base scaled to manufacture 240 tons/year of additional base and initially supply 2,400 tons/year of lunar materials to a 70 ton SMF would be capable of doubling in system throughput every 90 days. Earth launch requirements would be paced by supplying 10% of the facilites components and fluids from earth. The system would grow in approximately two years to the 300,000 tons/year throughput level comparable with SPS production. Initial investment could be low (5-10B$). A small space shuttle fleet could be adequate for the early transportation needs.

A 1980 ASEE/NASA summer study concentrated on two aspects of starting NTM industries with small initial installations (17). First, 200 terrestrial means (tools) of production were examined with respect to their usefulness in the space environment, advantageous use of solar energy, possibility of creating additional tools from local (NTM) materials (closure problem), and applicability to automation and/or remote control. Twenty-three of the basic manufacturing processes were identified which encompassed the four fundamental manufacturing processes (casting and molding, deformation, machining, joining). Eight production techniques unique to space were identified. Two different "starting kits" were then described which could use powder metallurgy techniques to replicate themselves or create a full heirarchy of the other tools of production. "Starting kits" offer the possibility of small packages which could be deployed on the moon or an asteroid

and operated remotely to construct much larger and/or more versatile facilities. The uses of cast basalts (from native soils) and mineral separation by means of electrophoresis were also examined. A second team considered the general aspects of systems which could be placed on the moon (100 tons initially) and replicate themselves using only local materials and solar power. Basic theory of automata allows this possibility. A scenario was developed of the general approach and a heirarchy of research needs was outlined.

Limited experimental work is in progress on direct electrolysis of lunar-like silicate melts (Haskin & Lindstrom in 15), glass and ceramic production (Mackinzie in 15) and anticipated by Rockwell International and CAL SPACE in previously proposed chemical process schemes (as in 4). Gravity swingbys of planets to modify trajectories and aerobraking (18) of spacecraft in planetary atmospheres can use NTM's to significantly increase mission capabilities to the plants. Obtaining propellants from NTM could also tremendously increase payload return from other planets and moons (Erstfeld et al. in 15; 19). NTM use could assist moon/space-based (radio) astronomy, solar photosphere (Sun Drive) probes, creation of hazardous "hot labs" in space, planetary surface exploration, and many other missions (20).

NASA (21) anticipates creation in 1981 of a program to utilize NTM's. Such a program could be the creative confluence of our available (and future) knowledge of the moon and other solar system resources and the full range of terrestrial technologies. From this program could flow the ability to send appropriate information and minimal hardware to other solar system objects and use local resources to organize some of the environment to our needs.

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