12 / A VISION OF LUNAR SETTLEMENT

MOST OF THE PAPERS in this book have addressed some limited aspect of establishing a manned base on the lunar surface. A few have taken an overview of the system required to emplace and/or sustain a surface facility. If one imposes a long range goal of true permanency, then certain technological and economic issues begin to emerge as key elements in the programmatic strategy. The high cost of access to the Moon must either be reduced by developing more efficient launch vehicles or else be circumvented by utilizing the lunar environment or resource base to augment the transportation system. Production of fuel on the Moon or installation of electromagnetic launchers for delivery of cargo to lunar orbit are examples of the latter. We have seen that achievement of closure in the life support system is a genuine technical challenge. Characteristics such as permanency and growth carry the implication of increasing organizational complexity, evolving management autonomy, and the eventual emergence of a culture. A number of scientists, engineers, planners, or scholars can claim to have pondered some one of these topics; very few have considered them in concert. Krafft Ehricke is one of the few.

Krafft Ehricke obtained a degree in aeronautical engineering at the University of Berlin where he also studied celestial mechanics and nuclear physics. As a teenager he founded a rocket society; two prewar patents of his dealing with rockets led to a transfer from the Russian front in 1942 to Peenemunde, where he participated in the development of the V2. After the war, he came to the U.S. and played a leading role in the design of the Atlas rocket. He is widely regarded as the father of the Centaur, advocating liquid hydrogen as a fuel when many thought it impractical. In 1965-1970 he began a series of studies entitled "The Extraterrestrial Imperative," introducing the concept of space industrialization. He published a three-part series under that title in the Journal of the British Interplanetary Society in 1977 and 1978. For the past 15 years he had been studying and writing on the subject of lunar industrialization and settlement, culminating in a book, *The Seventh Continent: Industrialization and Settlement of the Moon*, which is being edited for publication.

When we invited Dr. Ehricke to be a featured evening speaker at the Lunar Base Symposium in October, 1984, we were unaware of his serious illness. He eagerly agreed to appear and, despite our subsequent concern, made special arrangements for the difficult cross-country trip. I had never heard him speak and, like so many others in the audience, was enthralled by the panoply and the energy of his rich conceptualizations. Afterwards, I met him briefly and said that I felt like a student, working long and hard on a homework problem, finally to be shown the answer in the back of the book. Krafft Ehricke passed away at his home in La Jolla on December 11, 1984, a loss to us all.

Dr. Ehricke was working on the following paper at the time of his death, and it has been edited into final form by his long-time associate, Elizabeth Miller. The presentation of his ideas is at best a summary discussion, given the limitations imposed by our format. His forthcoming book will provide a more complete rendering. The paintings accompanying the paper are original art by Dr. Ehricke.

The facing piece for the section depicts Selenospheric civilization in 2062, during a return of Halley's Comet. Mare Orientale can be seen in the sunlit hemisphere of a waxing Moon. The network of lights on the earthward side represents Selenopolis, a fully developed lunar settlement. With a population of several million, it spans two million square kilometers, about one-fourth the area of the United States. Near the sunrise terminator are the lights of Cynthia, center of the Lunar Industrial Zone supporting mining, manufacturing, and power generation. The bright spots radiating outward from Cynthia are feeder stations, supplying raw materials from distant provinces. This section of Selenopolis, including slide landing strips for arriving traffic, comprises the lunar Technosphere. Expanding away to the horizon are the light of the lunar Sociosphere, a growing network of large multi-climatic and suburban housing for the Selenian population. On the horizon, at Sinus Medii, can be seen the bright lights of Novaterra, the large agricultural zone. During the lunar night, sections of Novaterra can be illuminated at an intensity of 0.6 solar constants by Soletta, an Oberth mirror swarm orbiting the Moon-Earth L1 Lagrangian point. The bright light near to and above Novaterra is an Androcell under construction in lunar orbit. This fusion-powered outer solar system research ship can carry a crew of thousands. The development of Selenopolis, and eventually the solar system, is open-ended.

LUNAR INDUSTRIALIZATION AND SETTLEMENT—BIRTH OF POLYGLOBAL CIVILIZATION

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This paper summarizes the major aspects of lunar industrialization and settlement. It identifies scientific and evolutionary facts leading to a definitive justification for why man must industrialize space, changing our present closed world into an open world. It defines three interlocking phases of open-world development: exo-industrialization, exo-urbanization, and extraterrestrialization. The Moon's environment and relative proximity render it the logical first location for this process to begin. Of all alternatives, the Moon offers the earliest, highest benefit relevance to terrestrial humanity and to the development of cislunar space. It is an invaluable proving ground for subsequent industrial developments and settlements in more distant, more expensive regions. Large orbiting space habitats should follow, not precede lunar development. A lunar development strategy consisting of five logical development stages (DS) is proposed. Their key accomplishments are summarized. DS-1 involves further synoptic prospecting for mineralogical provinces and candidate base site. DS-2 establishes a circumlunar space station, Moon Ferry, and automated laboratories and pilot facilities including an oxygen extraction plant on the surface. DS-3 establishes a first-generation nuclear-powered Central Lunar Processing Complex, and the first large-scale industrial production begins. DS-4 diversifies productivity by adding Feeder Stations in more distant metallogenic provinces. DS-5 establishes Selenopolis, a self-sustaining lunar civilization, founded on a powerful fusion energy base. Novel technological approaches are summarized, including the Lunar Slide Lander, Partially Enclosed Launch Track, the Selenopolis habitat, Lunetta, Soletta, and techniques for both mining, and helium and hydrogen production. Energy, transportation, products, markets, economic strategy and socio-anthropological factors are discussed. The central conclusion is the mandate for low-cost transport and energy, early self-sufficiency, early investment returns, industrial flexibility, and a systematic approach to creating a positive Earth-Moon balance of trade.

THE EXTRATERRESTRIAL IMPERATIVE AND LUNAR DEVELOPMENT

This paper sets forth key aspects of development of Earth's sister planet—Moon—as the first extraterrestrial world in this solar system. Its genesis is my book, *The Seventh Continent: The Industrialization and Settlement of the Moon*, which was written during the past ten years. It also considers a philosophy that I began developing in the early 1960s called The Extraterrestrial Imperative.

In the 60s, we heard statements like, "One square inch on Earth is more important than the entire surfaces of the Moon and Mars." But those who understood the long-term meaning of space not as a Roman circus or an ideological race between the United States and the Soviet Union realized that we will go into space precisely because that one square inch on Earth is so important. The space engineer is the environmentalist's greatest ally. Our work in space will change Earth's present closed-world environment into an open one with access to vast space resources and other critically needed benefits

that will greatly improve the lives of all people, and preserve Earth at its best—as man's home and garden for the maximum human future.

The philosophy of The Extraterrestrial Imperative is a definitive justification for a long-term future based on man's ability to transcend the limits of one small planet. This philosophy is definitive because it is supported by scientific and evolutionary fact. The facts show that a closed-world crisis is imminent but surmountable, that such a crisis occurred once before on Earth, and that the solutions came through technological growth.

After its formative period, the young Earth, like a giant flower, soaked up solar radiation in the form of chemical energy (C-H compounds) until the first primitive life stirred. Life's technological level (enzymes and metabolic processes) limited its interaction with the environment to processing fossil C-H energy and food sources by various primitive chemosynthetic procedures, mostly fermentation processes. When the previously generated organic resources ran out, the life forms began consuming each other. This had to lead to a survival crisis that was as certain as the fact that our dependence on fossil energy sources must eventually come to an end.

This was life's First Great Crisis on Earth. But what seemed to be an absolute limit to growth was no limit to growth. It was the beginning of a series of evolutionary technological advances that led to more growth. Metabolic advances in the photoautotroph led to the chlorophyll molecule and photosynthesis. These inaugurated the first industrial revolution on this planet. It was not possible then, any more than it is for us today, to be totally planetogenic. So life began processing solar radiation energy to chemical energy and thus for the first time used an extraterrestrial component. This made the interactive environment no longer planetogenic and chemical, but astrogenic and umbilical to the vast resources of the primordial inorganic environment—primarily water, CO_2, and solar radiation. Life had gained control over the production of its basic staples of food and energy. This changed the First Earth to the Second Earth, where, with the aid of the parasitic oxygen metabolism to reconstitute the comparatively limited supply of CO_2, a growing and expanding network of biological niches eventually culminated in the magnificent negentropic creation of the biosphere. Out of its womb arose, after a certain gestation period, the human being as the seed of the next higher metabolic capability: *information metabolism*. This includes the special abilities of information collection, abstraction, and reconstitution as knowledge and ability, which are storable in the human brain or devices developed by it.

Unlike oxygen metabolism, which is parasitic because its survival depends on plant/animal resources, information metabolism is umbilical—as is its forerunner, photosynthesis. The umbilical metabolism can interact between the negentropic sphere and the antropic wilderness on the outside. It need not be wholly dependent on organic fossil materials from one planet. Information metabolism can interact with the primordial environment and use inorganic matter, which is so abundant in the atom.

We all know what information metabolism has accomplished so far. It is the foundation of human civilization, including the industrial revolution that replaced slaves by machines. It is also the bridge to the cosmos. It can now enlarge our environmental base—not only for resources, but for growth in technology and, thereby, human existence.

The facts show that life now faces its Second Great Crisis on this planet. But life has, through advancing metabolic technologies, created open worlds. It will do so in the future because, for physical reasons, it can survive only in an energetically and materially open world. In an open world, there are no limits to growth. By capability and design, information metabolism can resolve the conflict that every umbilical metabolism has with the old environment. It can transcend the confines of one globe and become polyglobal. It has absolutely everything it needs to create a new and larger sphere of integration. I call this the *androsphere*.

While the biosphere is integrated by the chlorophyll molecule and photosynthesis, the androsphere is integrated by the human brain and information metabolism. The crucial difference between these spheres is this: the biosphere is integrated but non-modularized, permitting substances to move through everything—water, land, air—as is necessary for biotechnology to work. Biospheric technology uses some 20–25 elements and recirculates them because it is the only way to keep a materially open world. This non-modularized sphere is incompatible with information-metabolic technology—for example, nuclear technology. But the androsphere will be a modularized polyglobal structure without circulation through all parts. It is consistent with the evolutionary advancement of metabolic negentropism, and it is exactly what information metabolic technology and industry need to keep a materially open world. What is done in extraterrestrial environments does not necessarily effect Earth. By going beyond Earth, which is highly biophil, into environments that are largely technophil, we adapt the new environment to the requirements of information-metabolic androspheric technology. Building a selenosphere on the Moon is an example of androspheric modularization. Large habitats will be separated by vacuum from nuclear power plants, industrial plants, *etc.*, and what happens in these plants does not automatically drift into the habitats.

The technospheric evolution of life is clear in the main steps described. The sociospheric evolution has two analogues. In the biosphere, there are the species. In the androsphere, there are civilizations. Civilizations differ in different approaches to different things. But civilization is more. Civilization is ascendence beyond brutality, beyond the recognition of plurality. Civilizations will continue to be formed because they are dependent on infrastructural elements such as location, conditions, *etc.* Civilizations on the Moon and Mars will indeed be different from ours.

Taken together, these factors assure continuing growth—as long as we have an open world, and do not shy away from overcoming our problems by technology and *by our own development.* I must emphasize that technology is not the solution to our shortcomings. The solution is that we must grow and mature. But technology can make that easier. By contrast, a no-growth philosophy, which asks humans to live with less of everything, can regress us to the Middle Ages because a dog-eat-dog fight is bound to break out under such conditions. We have come too far. We have to go on. Life shows us that technological advancement is the road to take. But based on these technological advances, our species and civilization must advance also. Then we can proceed.

Based on the Extraterrestrial Imperative's epistomological infrastructure, I concluded at the end of the 1960s that three evolutionary phases of our expansion into space,

following initial exploration, can be substantiated:

Space Industrialization —the capability of productive existence in the new environment

Space Urbanization —the capability of establishing large-scale settlements and extraterrestrial civilization to the extent to which it can be underwritten by industrial and biotechnical productivity

Extraterrestrialization —a prolonged process of socio-psychological development and anthropological divergence, based on the integration and further evolution of the first two phases, manifesting itself in the physiological, anatomical, immunological, esthetic, and general cultural sectors.

Accordingly, I have urged for the past 20 years that we concentrate on the industrial development of space in the post-Apollo era, first in near-Earth orbits with commercial transportation and small space facilities, then on the Moon.

THE LOGIC OF LUNAR DEVELOPMENT

It has been said, "If God wanted man to fly, He would have given man wings." Today we can say, "If God wanted man to become a spacefaring species, He would have given man a moon." We are fortunate to be part of a double planet system, with a nearby sister planet whose surface conditions, despite all their differences from ours, still bear closer resemblence to Earth than do any other accessible surfaces in this solar system.

The Moon is the logical proving ground for subsequent industrial developments and settlements elsewhere. Only 2–3 flight days away, it allows us to develop at our very doorstep the experience we need to operate successfully and cost-effectively in more distant regions. No other celestial body and no orbiting space station can more effectively permit development of the habitats, material extraction and processing methods, and in essence, all the science, technology, and sociology required for a responsible approach to extraterrestrial operations.

Moon *vs.* Mars

The alternative of choosing Mars over the Moon as the first location for extraterrestrial development would take more time and money. We would first have to develop a new propulsion system, because it makes no sense to go to Mars by the skin of your teeth—barely making it after maybe 150 days, staying there 8 days, and rushing off again. The development of adequate heliocentric transportation would be an enormous investment, requiring additional acceptance of the high costs and operational risks associated with more widespread launch windows and longer transit times that still cannot compete with those of lunar flight. Moreover, we already have most of the technology required to get to the Moon and back. We don't need much more than oxygen/hydrogen propulsion, especially since we will be exploiting lunar oxygen.

Lunar Base *vs.* Space Colonies

The alternative of beginning with giant orbiting space "colonies" is not only unnecessary, but it is the wrong agenda. The reasons touch on a variety of facts of life about space

operations, ranging from concerns regarding the human to concerns regarding engineering, technological, economical, and other factors including investment returns. A brief evaluation of key differences between the orbiting space colony and the lunar base follows.

A lunar industrial facility will process lunar material *in situ*, precluding the need to transport large masses of raw materials for processing in orbit.

The weatherless lunar environment permits open storage of elements not immediately needed. This is preferable to the problems of mass distribution, orbital control, *etc.*, that stored surplusses would present to an orbiting facility.

The high vacuum and low gravity offered by the lunar surface are two key advantages for extraterrestrial industries. The high vacuum facilitates the generation and maintenance of cryogenic temperatures. One-sixth gravity (g) provides benefits for construction, transportation on and beyond the Moon, and operations. For example, the energy required to deliver cargo from the Moon to geosynchronous orbit and return to the Moon is 7.2% of that required for the same mission from Earth. Where 0 g is required, easily accessible circumlunar factories can be used. The energy to deliver cargo from lunar surface to orbit is less than 1/20 of that required for transport from Earth.

Apollo physiological experience shows that 1/6 g is a considerable, sufficient improvement over 0 g. One g is not needed and would actually be a hindrance. But higher g values can readily be generated centrifugally on the lunar surface. The lunar vacuum facilitates construction of very large habitat centrifuges equipped to house personnel for months at a time. The habitat centrifuge can run on magnetic cushions and be propelled by linear motors. It can provide habitats at 1 g, 0.4 g (in preparation for Mars missions), and at arbitrary levels from Earth-g to the g-levels on all other accessible surfaces in the solar system. At a radius of 1000 m, 1 g is generated at only 99 m/s = 356.6 km/h circumferential speed, or 0.95 rpm. It is, therefore, incorrect to claim that only one low-gravity level is available on the Moon.

The technophil lunar environment is favorable for powder metallurgical technology, electron beam and laser beam evaporation welding, and other advanced, efficient manufacturing processes. It is also favorable for the application of nuclear power, which is needed for the productive process to continue throughout the lunar night as a precondition for the economic viability of lunar operations. Lunar nights are for a major part illuminated brightly—up to 100 times the full Moon in the terrestrial sky—and are at least as suitable for mining, construction, and other outside work as are lunar days. But work at night requires an energy source that works at night, and the only one is nuclear

The need for protection from cosmic elements is another consideration. Orbiting facilities, especially if outside the radiation belt, are exposed to cosmic radiation, micrometeoroids, and solar proton wind from all directions (space angle 4π). But on the Moon, protection is offered from a space angle of at least 2π by the lunar mass. The use of topographical formations can increase the protective angle. Loose lunar material to provide protective shielding is abundantly available *in situ*. Lunar sand and breccia constitute suitable construction material. Breccia, sand, and dust are also the prime source of industrially valuable elements, and this fact greatly facilitates the mining of lunar crude.

Since raw materials prospecting, mining, and processing on a large scale are among the major objectives of space industrialization, permanent surface settlements are of course

preferable to space colonies. The concept of a Lunar Industrial Zone (LIZ) on the lunar surface is considerably simpler and more economical than the process of supplying a space facility in circumferential orbit from the Moon's various mineralogical provinces.

With a surface base, the establishment of large hydroponic agricultural facilities is also possible, based on encouraging results from preliminary tests of lunar material with plant growth. These facilities would use lunar bulk material enriched by nutrients imported from Earth.

Finally, the following additional comparisons between the lunar surface settlement and the orbiting space colony are of interest. These comparisons consider the mandate for a cost-effective, flexible, stepwise approach to the evolving complexities of integrating the three fundamental subspheres of an extraterrestrial settlement: technosphere, biosphere, and sociosphere. The technosphere includes all of the technological and scientific development. The biosphere includes plants, animals, people and everything they need such as food production, environmental controls, vehicles, and various machines, *etc.* The proper integration of these spheres will require advanced concepts in modularization that permit experimentation, change, and improvement as the expanding body of extraterrestrial experience dictates.

A large facility, especially a non-modular orbiting space facility, must be fully laid out and frozen without the benefit of adequate extraterrestrial experience by its population. This inflexibility involves many risks, and costly corrections, if possible, later. The internal architecture of large future extraterrestrial settlements cannot be frozen today because of the progressive nature of extraterrestrialization, its concomitant social changes, and advancing technologies. Moreover, it is not even clear that it will be necessary to simulate terrestrial conditions virtually to the last detail, including 1 g artificial gravity.

But the lunar surface is forgiving. The environment and the initial development of smaller habitat systems facilitates the learning process in construction and in the social development of relatively smaller populations of hundreds to a few thousands. This permits rational progression to larger settlements and populations of various races parallel to the growth of industrial, technological, and economic capacity, until the state-of-the-art is reached that permits the layout and construction of giant bio-niches, which I call *Selenopolis.*

In far-flung, modularized Selenopolis, with its variety of bio-environments and climates, new Selenian social structures and pluralities can evolve. They are not enclosed in a shell floating in a vacuum. Outside is a vast, challenging, magnificent wilderness—mountains, plains, horizons bathed in the light of day and Earth-lit night.

In a cylindrical space colony there are no horizons. From rising circular slopes, people watch people. If they step out, there is only a weightless, horizonless, unchanging sunburned void in which their little world is imprisoned. Their inside and outside environments psychologically promote ingrowth and involution.

The lunar environment promotes growth and evolution, since Selenians live in a world that supplies them with resources, but also is open to the universe. We might call them Cosmopolynesians, for they live at the shores of space. Space will lure them always, like the vast Pacific lured the Polynesians whose cultural main bases were on island worlds, not in tiny cocoons.

The most important aspect of lunar development lies in the human sector. It bears repeating that technological progress and environmental expansion are no substitutes for human growth and maturity, but they can help the human reach higher maturity and wisdom.

Human growth is contingent not only on the absence of war, or overcoming hunger, poverty, and social injustice—but also on the presence of overarching, elevating goals, and their associated perspectives. Expanding into space needs to be understood and approached as world development, as a positive, peaceful, growth-oriented, macrosociological project whose goal is to ultimately release humanity from its present parasitic, embryonic bondage in the biospheric womb of one planet. This will demand immense human creativity, courage, and maturity.

But the human is the violent product of violent evolution on a violent planet in a violent universe. As he enters space, he carries the tensions of our time and a heritage of endless wars involving hundreds of thousands of years of ideological, sociological, religious, territorial, and political hostilities. This heritage is frozen into humans like the solar magnetic field is frozen in the solar wind as it leaves the sun.

If the human is to outgrow this terrible heritage and grow with his expanding world, a few limited activities in near-Earth orbit and limited scientific expeditions are not enough. Really great tasks that penetrate man's social structure, infuse a broad evolutionary perspective, tax his creativity, and challenge his mind are needed. The industrial development of the lunar world toward the first polyglobal civilization is one such task—indeed the first logical goal on the agenda of the Extraterrestrial Imperative.

In summary, it can be correctly concluded that:

1. The Moon is much more than a quarry for orbiting facilities. It is a logical target for open-world development with a significant technological, productive, socio-economic, *etc.*, consequence potential.

2. Open-world development will involve a difficult trial-and-error process that must progress in steps. Compared to an orbital (open-space) environment, especially outside the protection of the geomagnetic field, the lunar environment is more protective, more conducive to stepwise development and experimentation, and more forgiving of failures.

3. The Moon is the logical first target for open-world development on which we can cut our teeth relatively conveniently and economically. Nothing can be done in a space "colony" that cannot be done sooner, more efficiently, and more economically on the Moon, if a few basic conditions are met.

4. Therefore, large space habitats, which I call *androcells*, follow, rather than precede lunar development. Their purpose is different, serving primarily as links in the development of other solar system worlds.

PRINCIPLES OF SELENECONOMICS

Lunar development must be rooted in a viable lunar economy, which I call *seleneconomy*. A seleneconomy can be viable only if its sustained cost-yield prospects are favorable.

Lunar development strategy should be dedicated to steps that maximize investment returns, minimize return times, and keep investment sizes manageable, so that venture capital and private investment can be attracted as rapidly as possible. The usual method of raising a demand for billions of taxpayers' dollars and decades of time before any alleged returns can be realized is economically not meaningful.

The investment strategy—if it is rational and disciplined—is in turn a major steering factor for the technological development that must be subjected to controlled-sized investment quanta, must assure minimum non-productive freezing of investment capital, and must contribute to reduced operating costs, especially logistics from Earth.

This renders "independence"-oriented investments and technologies particularly important, along with production- and productivity-oriented investments. Independence-oriented investments fall essentially into three categories (which in turn cut through various technological disciplines and affect the other two investment categories mentioned before). The three independence-oriented investments will involve:

- Use of nuclear energy, primarily for power supply rather than for transportation. Without nuclear power plants and possibly other techniques for all forms of industrial and agricultural production, a viable seleneconomy does not appear attainable.
- Reduction of terrestrial propellant supply through transporation energy management, lunar oxygen (LULOX) production, and LULOX depots on the Moon and in relevant orbits, especially geosynchronous and near-Earth orbits. Thus the terrestrial supply equivalent specific impulse is raised to over 3000 seconds, a value not attainable by modestly advanced nuclear drives.
- Extensive use of lunar materials for construction, for shielding, for growth of food plants and other purposes. (One proposed application is harenodynamic heat rejection—a novel technique for using lunar sand for heat rejection. On the Moon, this technique can eliminate the need for large, heavy, expensive radiators. It also broadens the choice of reactor types in the direction of lower operating temperatures, since the fourth-power law loses its overriding influence.)

In summary, maximum value generation capability and flexibility should be achieved with minimum initial expenditures and lead time. Only on this basis can lunar industry be developed early, effectively, and in a financially responsible manner. And only rising productivity and sustained economic growth can sustain an ever-increasing lunar population and the development of high Selenian living standards.

LUNAR PRODUCTS

The development of the Moon's resources will result in a lunar industrial output whose ultimate magnitude is impossible to fully anticipate. But it is clear that it will include raw stock from mining and refining, as well as a vast number of semi-finished and finished products.

Products will include sheet metal and trusses of aluminum, magnesium, titanium, iron, or alloys; castings, bars, wires, powders of pure or alloyed materials; glasses; glass

wool; ceramics; refractories; fibrous and powdered ceramics; insulation; conductors; anodized metals; coatings, including almost perfectly reflective sodium coating (since sodium can be freely used on the Moon and in orbits, whereas on Earth it reacts with water and is dulled by oxidation); thin film materials; silicon chips; solar cells; entire structures of various metals and alloys for lunar and orbital installations (they do not have to be made weather resistant); compound and fibrous materials; heat shields and insulation materials, as well as radiation shielding materials for space stations; propellant containers; entire orbiting facilities, such as space station and factory modules and liquid lunar oxygen depots; large portions of cislunar and interplanetary spacecraft; and so on.

Where 0 g is required for manufacturing, easily reached facilities in circumlunar orbit (CLO) can make crystal bole, fibers, solar cells and other special materials and products. Parts, components, subassemblies, and full assemblies can be integrated in CLO before being shipped to geosynchronous or other distant circumterrestrial orbits via electric freighters (which will eventually use lunar sodium as propellant).

PRIMARY MARKETS

Of all exo-industrial activities in geolunar space, lunar operations represent most closely a *total* industrial system. They are supported by carefully minimized, and eventually declining, non-selenogenic imports from Earth. In turn, they support orbiting and terrestrial industries with oxygen, helium, materials, products, and services. The four primary markets for lunar goods and services are described below.

1. Lunar surface. This market includes domestic demands for lunar industrial and habitational development; science and technology experiments for terrestrial customers; new forms of entertainment for terrestrial television viewers (low gravity, moonscape, and vacuum will permit "natural" special effects and later, new sports and cultural arts programs); and eventually tourism and retirement environments for Terrestrians.

2. Geosynchronous orbit (GSO). By 2000, GSO may hold well over 1000 service satellites that will be virtually indispensible socioeconomically. This market will demand spacecraft servicing; replacement parts; new components; partial or entirely new satellites; salvaging and recycling of inoperative systems, sections, components, and elements. In addition, LULOX filling stations may be established to reduce the cost of manned access or supply deliveries needed from Earth.

3. Near-Earth orbit (NEO). Orbiting manufacturing facilities will be likely buyers of lunar raw materials, capital equipment, entire production facilities, oxygen (not only for air but also for water—only hydrogen need then be imported from Earth, which means a large cost reduction), and eventually even some basic dehydrated foodstuffs.

4. Earth. This will be a major market for lunar raw materials, semi-finished products, and space-made components in larger quantities and involving larger masses than could be handled economically if the raw material should first have to be supplied from Earth to NEO manufacturing facilities. These lunar imports will sustain industries and create new job markets on Earth.

A LUNAR DEVELOPMENT STRATEGY

Lunar industry should be viewed as an organism that, over time, evolves to progressively more complex capabilities and generates sufficiently strong foundations for expansion. Lunar industry must be broad-based and diverse if it is to last. The need for economic feasibility and early returns will require a skillful interplay between market/customer-oriented products and services, and infrastructural investments such as transportation, energy, and surface/space installations that expand food production and diversify industrial productivity. Based on these considerations, on the seleneconomic principles mentioned earlier, and on basic evolutionary logic, the guiding principles of a lunar development strategy can be formulated:

Low-cost access to the lunar surface = low overhead and enhanced capability to provide services in geolunar space, due to low transportation and personnel costs.

Ample and low-cost energy assurance = high, cost-effective, and versatile value generation capacity.

Early self-sufficiency = low import costs, hence low operating costs and enhanced survival capability of lunar personnel.

Industrial flexibility = cost-effective means for increasing the capacity for diversification and adaptability to changes in market demands.

These principles have guided my studies since I called for the broad industrial use of extraterrestrial materials, specifically lunar materials, before NASA in 1971 and publicly, beginning in the late 1960s. They are designed to ensure steady progress; early economic viability through on-going productivity; and supply crisis resistance. (The latter ensures that lunar personnel do not have to return to Earth because they cannot sustain their lunar existence without basic inputs from Earth or do not have the "credit worthiness" to receive loans on the basis of a reasonably early payback capability—in principle, the situation that choked off the Apollo program.)

The Five Stages of Lunar Development

The lunar industrial establishment is likely to consist of two basic components: the Lunar Industrial Zone (LIZ) on the surface and an orbiting component, the Lunar Industrial Space Installation (LISI), in low CLO. Together they offer in one relatively small cosmic space the before-mentioned wide range of gravities, natural and artificial.

My studies have resulted in a number of novel technological approaches to lunar industrialization, as well as a consistent lunar development logic whose basic framework is briefly described here. There are five development stages (DS). There is an associated economic and industrial rationale for the transition from one DS to the next.

The achievements of each DS belong to one of three main sectors: *technosphere* (research, technology, industry); *biosphere* (plant/animal life, food production, general plant growth, selenobiosphere); and *sociosphere* (habitats, living and working spaces, society, economy, politics, and culture).

Stage One

DS-1 could be accomplished in this century. It involves synoptic prospecting to further detect metallogenic or mineralogenic provinces and obtain other advanced information for industrial site selection. Simplified Surveyor-type landers and at least one lunar polar orbiter can be used. Emphasis should be placed on sites in the western and far-western part of the near-Earth side north and south of, as well as at, the equator. This area holds promise as a base site not only due to its potential for resources, but for a variety of other reasons. These include its ready, low-cost Earth communications and transportation accessibility, and a flat area between 50° and 60° western longitude at Oceanus Procellarum. This area appears particularly suitable for what I call a slide landing strip, which would in turn influence the location of the first Central Lunar Processing Complex in DS-3.

DS-1 would also include establishment of a Lunetta reflector orbiter to illuminate the perpetually shadowed places at high latitudes and the polar regions to permit photography, cartography, and the possible identification of polar ice deposits, if any.

Stage Two

DS-2 is an important, cost-saving and indispensible preparation phase for those who will become "first generation" ground personnel. It involves further work toward surface base site selection and operations training prior to lunar base build-up.

A Circumlunar Space Station (CLSS) is established in ~100 km equatorial orbit and uses a Moon Ferry (MF) for limited manned surface missions. The CLSS serves as habitat, operations and training center, and laboratory for engineering, biological, and medical purposes. It will support experimentation with much larger quantities of lunar materials than could be economically delivered from the Moon to Earth. Most lunar materials will be brought from the surface to the CLSS by automated returners. The results should lead, about halfway through DS-2, to selection of the appropriate surface base site.

Experience in this DS will also provide medical and behavioral profiles of personnel who will spend time in the two worlds of lunar surface and space station and who will experience prolonged stay in orbit about another body, remote from Earth.

DS-2 continues with establishment of sophisticated, automated laboratories and pilot facilities on the surface. Modules are mailed from Earth to the selected base site. Using the MF, CLSS personnel descend to set up, start, and maintain the systems.

One of these systems can be the first small-scale automated oxygen extraction plant, providing gaseous O_2 for MF and CLSS. My version works on the basis of induction heating a mixture of lunar dust/sand and hydrogen, and on the formation of water and its electrolytic separation to oxygen and hydrogen. The latter is recycled. The former is stored in chilled, moderately compressed form. By omitting the liquefaction facility, the system is simplified. It consists of H_2 dust reaction chambers, H_2O condenser and storage container, electrolysis module and storage containers for H_2 and O_2. Powered by a 100 kWe M_{OU2} space reactor, the system produces about 2.8 t water in 22 (24-hr) days out of 11.9 t lunar dust, and generates electrolytically about 2.5 t O_2 in the remaining 8 days of a 30-day month.

A 10-person lunar crew consumes about 300 kg O_2 per month, so at least 2000 kg/month could become available for propulsive purposes.

Other modules placed on the Moon during DS-2 can permit personnel to stay on the surface for weeks at a time. Figure 1 shows two laboratory/habitat modules and, in the background, a nuclear power station. Surface operations made possible by the existence of these and other modules will build a wealth of crew experience for work that will begin in DS-2 and further evolve during DS-3.

While existing transportation capabilities will be used to the maximum extent in this no-frills lunar development approach, DS-2 must be accompanied by major strides in research, development, testing, and engineering of special, highly cost-effective transportation systems for use in later DS.

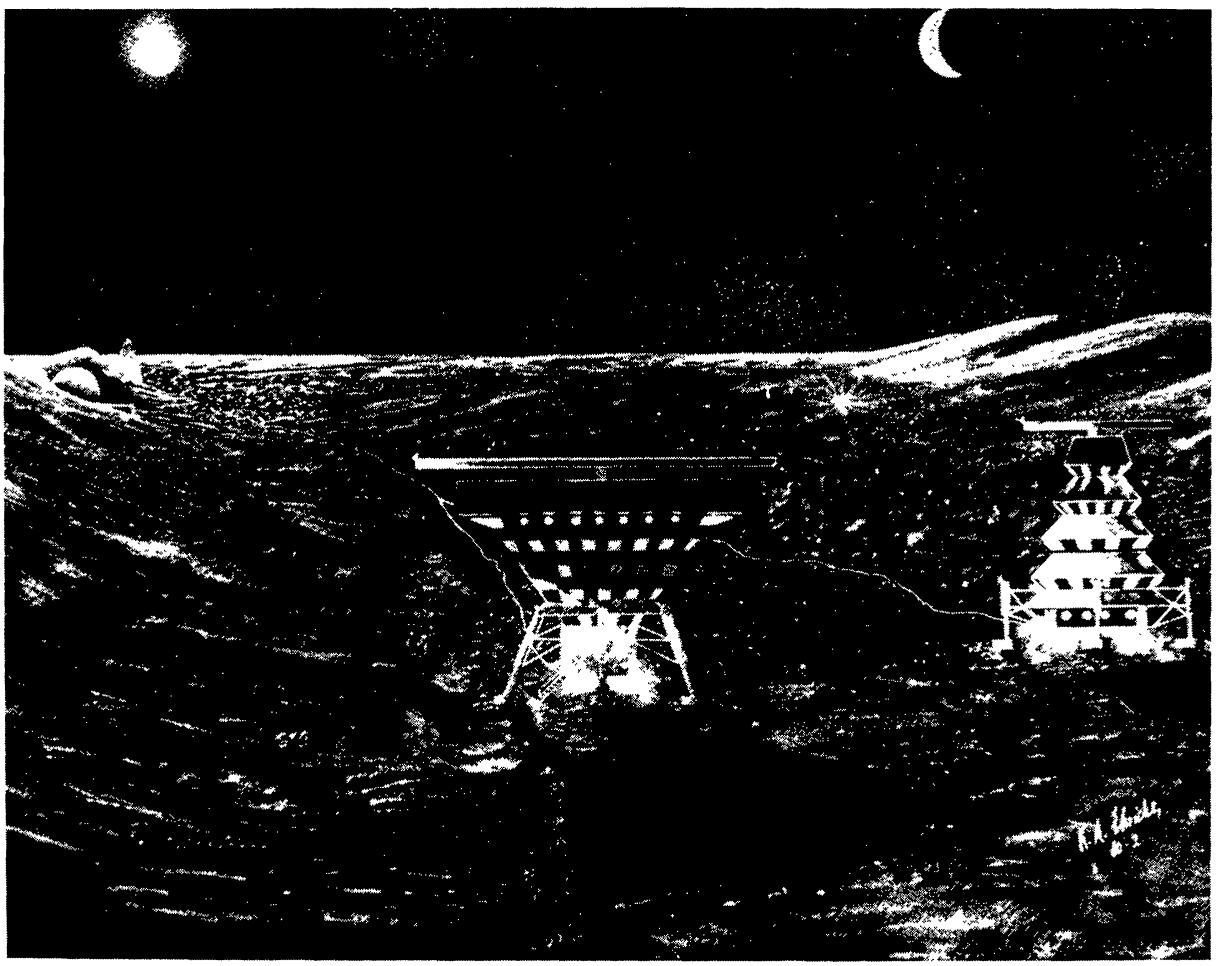

Figure 1. First-generation lunar surface crews get started in laboratory/habitat modules mailed from Earth. The inverse converging shape of the modules maximizes shielding against corpuscular radiation, optimizes temperature control for placement in equatorial regions, and serves as an umbrella to provide shade in the module's immediate vicinity.

Stage Three

The transition from DS-2 to DS-3 initiates the operation of lunar industry. The payoff on initial investments begins here, at first modestly. This payoff is a prerequisite for expansion into larger-scale industrial production in DS-4, whereby lunar profitability will assist with the larger investments for the next stage, and will demonstrate credit-worthiness for attracting major terrestrial investment capital.

A first-generation nuclear-powered Central Lunar Processing Complex (CLPC) called "Cynthia" is established where there are favorable conditions for a slide-landing strip and for finding valuable raw materials nearby. As indicated earlier, a promising location for Cynthia is in the far western Oceanus Procellarum at the equator, just east of the south rim of Hevelius. It is not likely that this location contains higher concentrations of all desired minerals, if such a place exists at all. As Cynthia's production diversifies, minerals will have to be exploited in other places using Feeder Stations (FS) to be established in DS-4, since it would be uneconomical to place CLPCs at several locations.

Cynthia will first produce oxygen, then other materials. As a result of experience gained during DS-2, lunar personnel will by now have developed expertise in handling tools, equipment, and construction work. The latter will include cold-welding cut lunar rocks; producing lunar bricks and possibly cement with lunar sulfur as binder (instead of water); and compacting lunar fines (powdery to coarse sandy material) into building blocks for lunar igloos, or better, ligloos. These ligloos will have sprayed airtight inner liners and airlocks—providing shirtsleeve shelters, workshops, and "greenhouses" for growing food plants.

Crews will also manipulate teleoperators and supervise robots under various conditions, day and night. They will perform cold welding, laser and electron beam welding, surface mining and drilling. They will monitor and maintain a wide variety of equipment and agricultural modules.

Thus trained, the first-generation lunar crews can schedule Cynthia for production runs of oxygen, silicon, aluminum, iron, glasses, and other materials. From these raw materials, Cynthia can progress to powder metallurgy, vapor phase metallurgy, production of solar cells, computer parts, and eventually space habitat structures, communication platform stuctures, antennae, service satellite parts, reflector structures, and much more.

DS-3 will also involve the introduction of novel transportation arrangements that radically lower the costs of getting to and from the lunar surface and across cislunar space. The CLSS of DS-2 grows into a staging base, training second-generation selenauts and expanding into a 0 g factory.

Stage Four

DS-4 marks the expansion of industrial production and services. Diversification grows beyond extraction and semi-finished products to finished products and assemblies. Strategic economic positions must be attained for supplying orbital and terrestrial markets, yielding a high gross lunar product that not only builds a positive balance of trade, but also builds the infrastructure and establishes credit-worthiness for continuing expansion.

To broaden market response capability, Cynthia is augmented by FS in valuable, sometimes distant provinces identified during DS-1 and 2 as having an abundance of certain raw materials.

The FS are highly automated and basically simple. Most are unoccupied or intermittantly occupied. They are remotely controlled and operated from CPLC control by laser communication link via communication relays. The relays float on the supporting pressure of microwave beams, as would a ping-pong ball on a water jet. They are placed at appropriate altitudes, depending on FS distance. This communication concept precludes the need for either a satellite, which is interrupted by precession, or a tower, which would have to be 20 or 30 km high to maintain the connection. (The concept is also extremely practical for communications anywhere on the Moon, including control of electromagnetic trains, *etc.*)

Materials collected at the FS can be transported to Cynthia by various methods, depending on distance. Relatively close FS, say 120 miles away, can send cargo by electric cars. The most important FS can eventually deliver via high-speed electromagnetic trains. Meanwhile, distant FS can hurl cargo ballistically to receiver craters near Cynthia with great accuracy, thanks to low lunar gravity and high vacuum.

My design studies have considered a large number of ballistic systems for cargo transport. I am most favorably impressed by the suitability of a centrifugal launcher with curved launch tubes. It runs on magnetic cushions propelled by electromagnetic bilinear motors.

DS-4 also includes installation of fusion power plants and initial build-up of a solar reflector swarm, "Soletta," in L-1. Eventually, Soletta will reach the size of 120,000 km^2, illuminating a 200,000 km^2 area at lunar night around Sinus Medii for agricultural and biospheric purposes (Novaterra). Biospheric Novaterra and technospheric Cynthia become the pillars on which sociospheric Selenopolis and lunar civilization rest.

Stage Five

DS-5 establishes Selenopolis and the selenosphere—a fully developed lunar world with a large population underwritten by industry. This stage is contingent upon a strong economic foundation, a very high degree of self sufficiency, particularly in food production, and a powerful fusion energy base. Initially, it will require more massive imports from Earth. But its expansion should be commensurate with economic growth and the ability to sustain corresponding population increases, thereby financing its evolution to a high degree with lunar capital.

With this premise, we move into the twilight zone between economics and politics. Analysis of pertinent factors—social, economic, and the onset of the social and cultural extraterrestrialization process—suggests the inevitability of this development. Thus in DS-4, the issue will arise concerning the extent, in DS-5, of financing and controls by terrestrial institutional power.

As defined here, DS-5 is a state in which trade relations with Earth are based on rough commercial equality. This means mutually complementary value generation, where lunar civilization is not in a receiver position *vis-a-vis* Earth. The resulting high level of

fiscal and economic self-determination, and the attraction of terrestrial investment capital, cannot help but encourage political implementation. Therefore, much will depend on lunar political status and prospects by the end of DS-4: will this be a colony of Earth, part of the common heritage of terrestrial mankind? Or will it be an independent political entity with Selenians in control of their own world? On a foundation of fusion power, the vast potential of the lunar economy renders the latter alternative possible and hence likely.

DS-5 progresses in a series of steps involving increasing advancements in industrial, agricultural, and energy production, in transportation, and in habitats. The early habitats are envisioned as a series of small units hugging the inside walls of a crater. But Selenopolis—the city-state of lunar civilization and the lunar biosphere—will be a network of enclosures gradually expanding to cover many square miles of the lunar surface, and some parts of the subsurface.

The enclosures comprise sections that are several miles long, with interior dimensions of 3200 feet across at floor level, and 1600 feet high to the center of a curved ceiling. The sections are joined at nodal points that serve as power, supply, and climatic control centers.

Selenopolis embodies urban, rural, agricultural, industrial, and resort areas. Each section is separated from the other by a solid but transparent "curtain," because each has a different Earth-like climate and season. Normal atmospheric conditions for Earth are maintained. In the beginning, simulated Earth climates will include continental, dry subtropical, and semi-arid, with climatic cycles where applicable. Other sections will have climates that are adjusted to their special agricultural functions in order to maximize plant growth (measured as yield per unit area and number of crops per annum). This will be accomplished primarily through CO_2 enrichment of the atmosphere, and by temperature, humidity, and suitable irradiation cycles, all coordinated to achieve the optimum combination. Figure 2 shows an agricultural zone.

Resort areas can include a winter section with snow, a subsurface lake for boating, a "sunbelt" with "lunar desert" views from a clubhouse that also overlooks the Alan B. Shepard low-gravity golf course, *etc.* Selenians may also enjoy the Krafft A. Ehricke rotating swimming pool.

Selenopolis interiors are illuminated by sunlight reflected through the ceiling by a mirror system. Since a lunar day is 14 Earth-days long, some of the mirrors are colored to provide the same time changes and sky colors experienced on Earth from morning to night and from season to season.

Selenians will not be bound to their biological environmental niches. In comfortable space vehicles, or in transport vehicles with interior shirtsleeve environments, they can tour the coasts of mare, the mountains, the cliffs of the southern highlands, the province of large craters stretching from the eastern coast of the Mare Nubium to the South Pole, and more.

With establishment of Selenopolis, the development of lunar habitation reaches its conclusion in the sense that a new environmental niche—a lunar biosphere honeycombed with ecological niches—has been created. But Selenopolis is open-ended, growing with

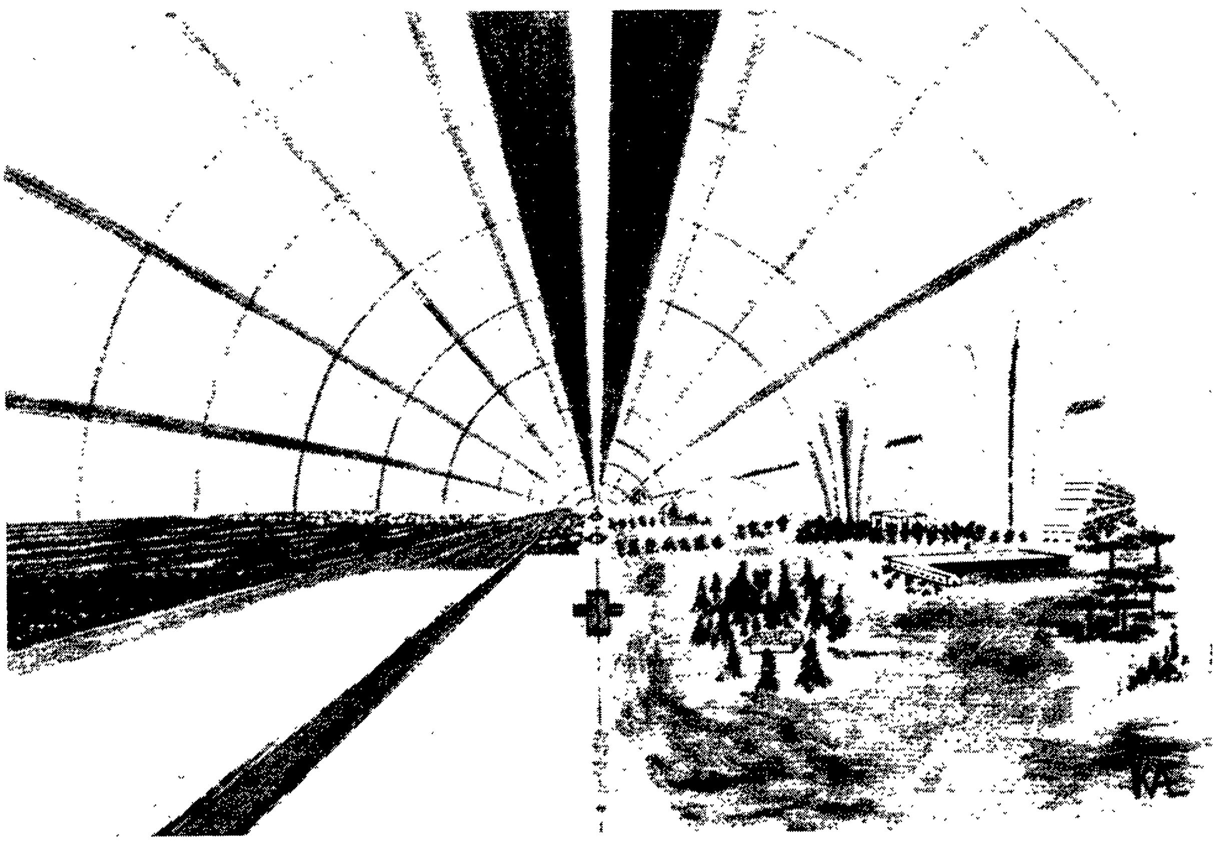

Figure 2. A large agricultural zone in Selenopolis is accented by occasional high-rises whose unconventional shapes are permitted by lunar gravity, maximizing the use of surface space.

its population and advancing technologies. In principle, the overall complex could eventually house many hundred million people. Such a large complex is never completed, just as development of a continent is never completed. Like the giant cathedrals of the Middle Ages, Selenopolis will be the work of many generations.

ENERGY

Selenopolis cannot be built with yesterday's technology. For economy, and because of the long lunar night, fusion energy is as fundamental and as indispensible to the Selenosphere as the Sun's energy is for the terrestrial biosphere.

The lunar environment is exposed to the nuclear influences of the Sun and the cosmos, and there are no liquid or gaseous means for circulation. The absence of any circulations makes the Moon suitable for the installation of nuclear power plants and for the underground use of nuclear energy, uniform or explosive. Nuclear technology will destroy no natural balance. It is most effective because it has the lowest entropy and mass. The open, peaceful use of nuclear energy, including release of nuclear detonation energy underground, is permitted by the International Treaty on Outer Space (1967).

Large deuterium-tritium (D-T) fusion power plants are the logical lunar base power source for many reasons. Their operation is easier on the Moon than on Earth because of high lunar vacuum. For example, the lunar vacuum facilitates maintenance of a high vacuum in the plasma chamber without size restrictions, reducing neutron flux density per unit of wall area, thereby reducing associated wall erosion and embrittlement, and impurities. It also simplifies reactor construction and maintenance and facilitates the use of superconducting magnets.

The D-T reaction is the comparatively "easiest" realizable fusion reaction. Most importantly, an excess of tritium can be bred and stored in the D-T reactor, decaying into Helium-3 (He-3) and an electron. This extremely rare helium isotope is practically non-existent on Earth. It is an important fuel for a D-He-3 fusion reaction.

After the D-T reaction, the D-He-3 is the next more difficult fusion process to attain. But as soon as the D-T reaction is operative, it becomes important for terrestrial fusion technology to advance to the D-He-3 reaction, because no radioactive tritium is employed and the reaction is almost completely "clean." Only about 7% of the released energy is carried away in neutrons, so virtually no radioactive isotopes are generated. The reaction essentially produces protons and alpha particles, that is, charged particles that can be confined magnetically. Wall-loading problems practically disappear, resulting in greatly improved power plant economy. Moreover, the proton-helium reaction plasma is a highly valuable resource for processing heat for material extraction and waste recycling, as well as for generating further electric power. Therefore, it will be highly desirable to develop the techniques for generating the higher temperatures needed to ignite a D-He-3 plasma.

But the He-3 must be produced somewhere, and the Moon is the best candidate. Therefore, large D-T fusion power plants become not only the chief power source for lunar industry and civilization, but valuable fuel factories supplying He-3 for terrestrial use and for use by interplanetary and possibly cislunar spacecraft. D-T plants should begin operation in the latter part of DS-4, D-He-3 plants in DS-5. D-He-3 power plants are also of interest because the proton output, combined with the electron output from tritium decay and with lunar electrons, forms hydrogen.

If Earth depends on the Moon for its He-3, the Moon depends on Earth for its deuterium and lithium—a case of mutual self-interest, which historically has formed more enduring and reliable arrangements among peoples than ideology or idealistic cooperation.

A 1,000 gigawatt-year (8,760 billion kilowatt-hours, almost four times the electricity consumed in the United States in 1980), generated by a D-T fusion reaction at a thermoelectric conversion of 0.33 and a triton yield of 2, produces 168.9 metric tons of excess tritium. Of that about 84 tons are converted to He-3 12.3 years later (and more each year thereafter, if the D-T fusion process continues at that level or increases). Eighty-four tons of He-3 suffice to generate more than a 500 gigawatt-year in D-He-3 fusion reactors on Earth at a profit of $44 billion annually per $0.01 of profit on the kilowatt-hour.

In terms of mass, the supply requirements are no problem at all, because of the extremely low entropy level of the fusion plasma. For the generation of a 1,000 gigawatt-year at 100% efficiency, 112.6 tons of deuterium and 777 tons of natural lithium are

consumed annually, assuming a yield of 2 tritons for each triton burned. If the fusion reaction operates at 50% efficiency and if in this case all the unused deuterium is lost (an unlikely possibility), 225 tons of deuterium must be supplied to the Moon annually.

In the first case, the transportation requirement is a modest 13 ascents annually with a derivative of the Shuttle at 68-ton payload. In the second case, it is 15 ascents at a cost of about $1 billion plus procurement of the deuterium and lithium. Selling He-3 can therefore be quite profitable for the Selenian economy and is an example that demonstrates the continuing growth from DS-2 through DS-5.

At a conversion efficiency of 0.33, which is very conservative considering this state of technology, the waste heat per 1,000 gigawatt-year of a D-T power plant complex amounts to some 4.1×10^{13} kilocalories per 24 hours. This is enough energy to warm the atmosphere in almost 155 km^2 of 1,000 m $\times$ 500 m Selenopolis half-cylinders, from 0°-25° C or to heat 2 billion tons of water by 20°C. Because of insulation and thermal flux control, one such power complex could climatize a 30,000 km^2 sector of Selenopolis, capable of accommodating a population of one to ten million (at U.S. to European population density).

NUCLEAR POWER FOR RESOURCE EXTRACTION AND PROCESSING

Extraction of the Moon's raw materials will involve separation and refining. Processes using electrolysis, chemical, or thermal methods reduce, and can also be used to separate, different semi-metallic and metallic minerals from each other. Electrolysis poses high energy requirements. The thermal-mechanical method involves centrifugal separation after elements or compounds are partially or completely melted. Chemical reduction is complex and requires carbon and hydrogen. These chemicals would have to be imported from Earth because they are not initially available in relevant quantities. But abundant low-cost nuclear energy can be. The issue is adequate processing heat at the lowest possible cost.

The sources of heat for reduction are, in order of increasing temperature: the high-temperature reactor (HTR), with reactor cooling gas outlet temperatures of 900°-950° C; nuclear-electric arcs (these are less suitable for quantity production); solar concentrator-heater ovens, for temperatures up to several thousand degrees and low mass requirement (these are inoperative, of course, during the 354-hour-long lunar night); underground atomic ovens (UAO) stoked by small fission or fusion detonations; and the plasma from a fusion reactor, once this technology is developed. For early application and high-mass flow, day and night, the HTR and UAO are the most effective methods, besides solar heating during the day.

Figure 3 shows a typical arrangement for a strip mining-beneficiation-refining facility. It uses electrolytic and thermal-centrifugal, as well as other reduction and separation furnaces. Strip-mined lunar crude is fed into the furnaces by conveyor belts that also serve to transport tailings and slag back to the strip mine zone. The entire system is powered by a pebble bed thorium HTR that breeds U-233 fuel from thorium-232, thus

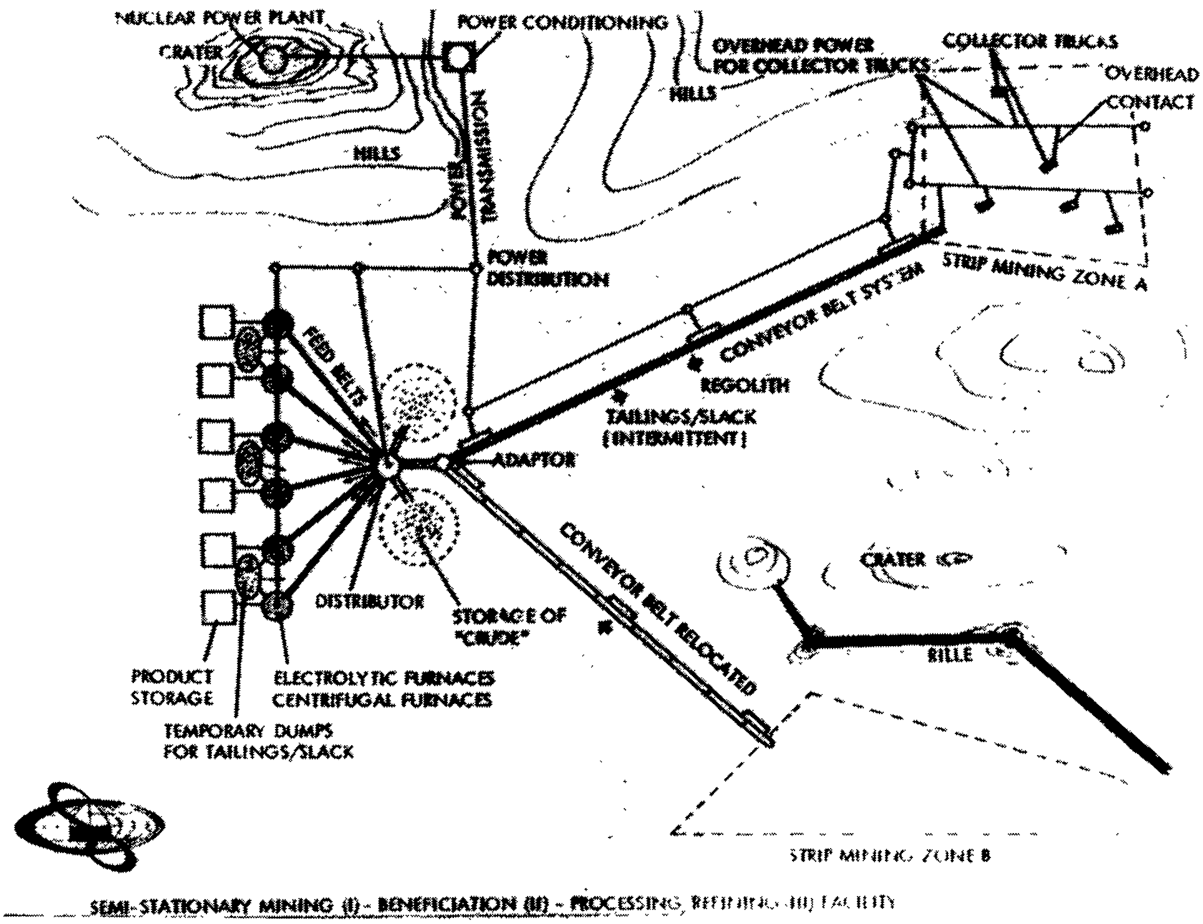

Figure 3. Lunar Development Stage Three includes establishment of the first strip mining-beneficiation-processing/refining facility as part of the Central Lunar Processing Complex. Surface mined material is sorted and fed into furnaces. Metals, silicon, and other outputs are removed from the furnaces to storage as industrial feedstock for semi-finished and finished products, for transport to circumlunar orbit and further processing at 0 g, or for export to customers in circumterrestrial orbits and on Earth.

avoiding production of the more dangerous plutonium-239. Later, a combination of a thorium breeder HTR and molten-salt reactor (MSR) will be used; the former using the excess to generate more electricity. The MSR is in some respects even more convenient to maintain than the pebble bed HTR.

The nuclear power facility will be located at some short distance in a suitable crater or canyon, whose walls provide safe shielding.

NUCLEAR PULSE TECHNOLOGY FOR UNDERGROUND DETONATIONS

Since my first publication on lunar detonation mining in 1972, I have investigated a broad variety of operational modes for this technique. Only a brief overview can be presented here.

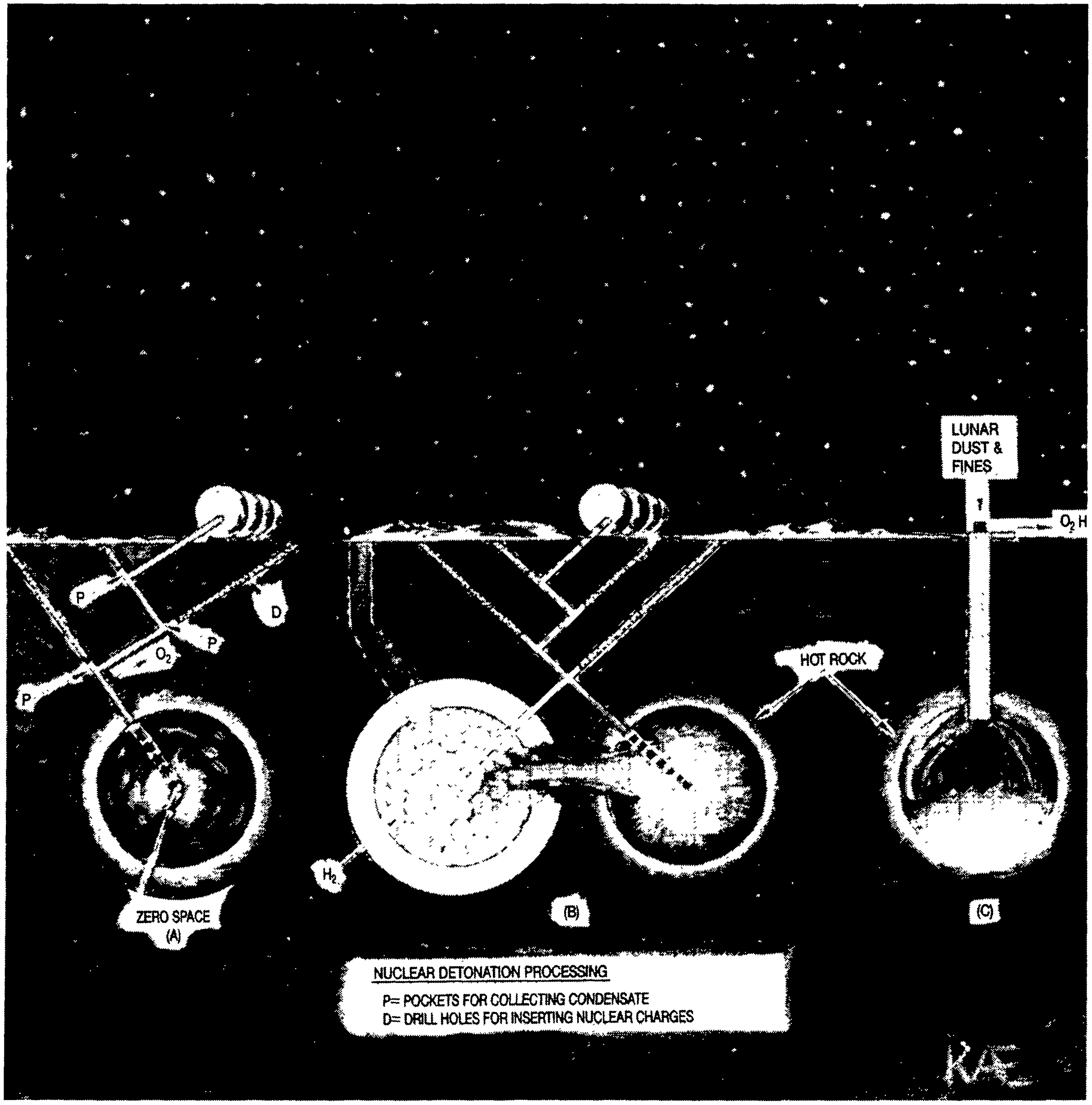

Figure 4. Three operational techniques for lunar underground mining made possible by small nuclear detonations.

Fortunately, the Moon's crust is much poorer than the Earth's in elements that could be turned into undesirable radioisotopes by neutrons released during an underground nuclear detonation. The detonation process itself releases radioisotopes if it is fission. Fusion detonation is preferable.

Figure 4 depicts three operational techniques for nuclear detonation mining in underground caverns formed by small nuclear detonations. The caverns are blasted in bedrock (solid mare basalt, a pre-Imbrian rock). Because of the rock's total dryness, there is no steam generation to crack the cavern walls (as would occur on Earth, leading to collapse of the ceiling). Detonations in this environment produce highly compressed,

glassy walls. They may be so water-impermeable that the cavern could be used as a water reservoir without the danger of losses.

After blasting, the initial nuclear detonation heats up the interior lunar rock. This produces intense thermal radiation from the walls, since their heat conductivity is poor by terrestrial standards, and the heat remains concentrated in them. This means that the detonation energy is essentially dissipated productively in the processed material. Radioactivity declines rapidly after a detonation and is at a minimum when mining begins. Moreover, the mine is cleared out by robots. The mined, deoxidized material itself is not radioactive and can readily be handled after removal.

Figure 4 shows, at left, single-detonation oxygen extraction; in the center, a technique for absorbing detonation-produced oxygen with other elements to produce life-supporting and industrial materials; and at far right, an atomic oven.

Lunar crude is fed into the atomic oven from the overlying loose breccia layer, either as fines and sand or as crushed breccia, to provide a maximum surface-to-mass ratio for maximum outgassing (reduction) efficiency. Oxygen evaporates out, and the deoxidized elements form an enriched ore, which may subsequently be separated into its constituents.

A more advanced UAO arrangement can involve a series of ovens, sequentially alternating between hot state for gas extraction, and cold state for mining the reduced material. There is practically no limit to the amount of lunar materials that can be processed annually by a combination of UAOs and nuclear-electric power plants.

TRANSPORTATION

While production of low-entropy fusion energy becomes a major consideration during later DS, the first prerequisite for lunar development is low-cost Earth-Moon transportation and low-cost transportation between the Moon's surface and circumlunar orbit. This must involve maximum use of existing Earth-Moon transport capabilities, along with development of a novel class of vehicles, facilities, and techniques that use the unique lunar and cislunar environments to advantage.

The Diana Fleet

A fleet of ships is needed for carrying out all aspects of lunar and cislunar development. In DS-1 and 2, the payloads required for lunar prospecting, establishment of the CLSS, and pilot surface facilities can be delivered to the Moon and CLO by combinations of the Shuttle, a Shuttle derivative (the Heavy-Load Launch Vehicle, HLLV), and Centaur. The latter will be modified to fit the Shuttle orbiter payload bay and is referred to here, unofficially, as Centaur II. The Centaur design allows sizing for various mission requirements. With a small maneuver module for lunar capture, it can deliver between 5.6 and 12 tons into circumlunar orbit, providing adequate capability for one-way transport of automated systems.

In DS-2, Shuttle capability is assumed to be increased to that of the HLLV and Centaur II to a cluster of rockets as drive for a large, first-generation Geolunar Transport-I to establish the CLSS. DS-2 would establish two new transportation systems—Moon Ferry and a highly cost-effective nuclear-electric geolunar freighter.

In DS-3, the advanced HLLV is still adequate. But an enlarged Geolunar Transport-II is needed, along with a LULOX filling station in CLO. The chemical transport should be designed for the Hohmann Braking Maneuver (HBM), single-module version. It should have variable thrust and modular design to permit as many geolunar transport functions as possible.

My key conclusion after extensive investigations concerning chemical transports operating between NEO and CLO is that the flight modality is the key to the relation between launch mass in NEO and cargo capacity as well as vehicle propellant load. A flight modality without HBM and without LULOX would shift an economic development of the Moon far into the future.

The decisive factor is not the limited reduction in propellant and launch cost possible with Earth launch vehicles. It is the cost-effective geolunar flight modalities with correspondingly designed interorbital transport vehicles (IOT). A flight modality involving HBM alone already yields a decisive improvement in cargo capacity. At first, the HBM advantage is economical for delivering to the Moon the freight needed to build a LULOX production capability. But the heavier deliveries required for Earth-Moon transportation involve the burden of carrying all the needed oxygen from Earth; therefore HBM cannot be used. The solution will be LULOX filling stations in NEO as well as CLO. The economic superiority of a LULOX modality lies not in an improved freight-carrying capacity, but in a decisive reduction of the Earth-NEO supply requirements, hence transport costs.

The most economical modality uses both LULOX and HBM. It yields the lowest propellant factor for a geolunar round-trip with chemical propulsion, because only hydrogen needs to be supplied. This corresponds to a supply I_{sp} of 12,400-15,200 seconds, which could otherwise only be attained by a very advanced nuclear propulsion system.

For cost-effective supply of a LULOX depot in NEO, a specialized LULOX freighter capable of HBM is required. It will bring LULOX as slush that is allowed to thaw slowly during transit, reducing evaporation losses.

For cislunar space operations involving missions between CLO, GSO, and 48-hour orbits, solar-powered electric propulsion systems will provide superior payoffs. They are ideally suited to this region because it has negligible Earth shadow effects, no radiation belt effects on photovoltaic cells, and very weak gravitational forces. At a given service life of the electric propulsion system, more round-trips can be made between CLO and GSO or 48-h orbit than between CLO and NEO, and more cargo can be transported. Cislunar freighters are also suitable for transporting service personnel to maintenance jobs in GSO and back to their lunar homes.

In comparing ion and magnetoplasmadynamic (MPD) drives, the latter show certain advantages, such as three orders of magnitude higher thrust density and potentially longer thruster operating life.

The Lunar Slide Lander

If lunar transportation is based on oxygen/hydrogen, and if LULOX is used, the price for this advantage is the cost of importing H_2 from Earth. It is therefore of vital importance to minimize this import. Fortunately, this can be done.

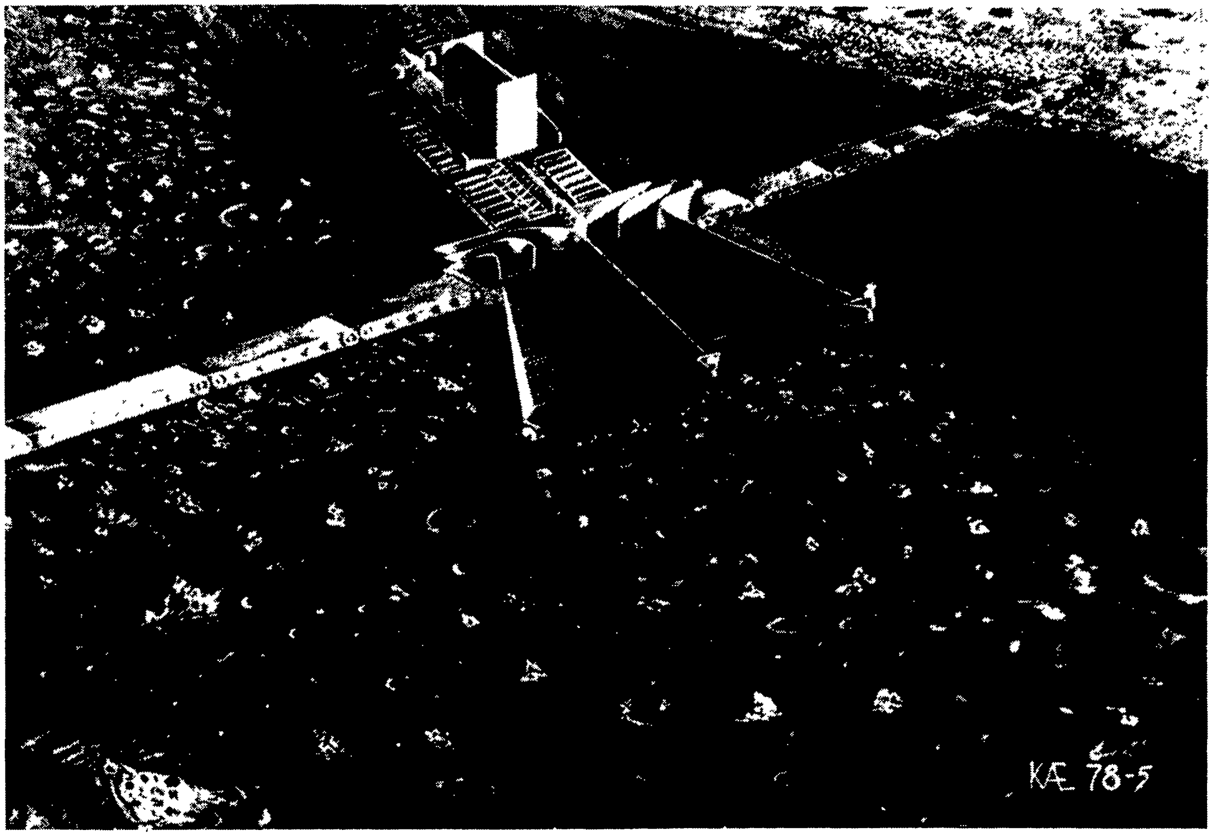

Figure 5. Nuclear-powered sweeper, designed for 1/6 g, prepares and maintains an 80-km-long runway for the Lunar Slide Lander.

Conventional lunar descent and ascent are prime consumers of H_2. But for ascent, there is a way to capture and reuse the H_2 (see next section). And for descent, the amount of H_2 required can be reduced to a fraction of that used by conventional systems.

A new concept, the Lunar Slide Lander (LSL), is proposed. It lands on a long, flat area and transfers its momentum to the lunar surface material, thus requiring very little propellant to land. This concept is not only decisively cost-saving, it avoids release of increasing exhaust gases as lunar traffic grows, preserving the Moon's valuable high vacuum for cost-effective ascent and for industrial uses.

In the DS-3 discussion, it was suggested that Cynthia, the Central Lunar Processing Complex, be established in the far western part of Oceanus Procellarum because, among other reasons, a flat area for slide landing exists. Covered with dust and sand, it can be turned into a suitable landing strip with little preparation. I envision a landing strip sweeper (Fig. 5) that can easily cleanse the area of larger stones down to do a depth of 20–50 cm. My calculations show that the LSL braking surfaces go down only a few centimeters.

Touchdown at velocities of up to 5500 km/h, bringing the LSL to a halt along an 80-km-long landing strip through interaction with glassy-sandy material, introduces a new branch of spaceflight dynamics, for which I propose the term *harenodynamics* (from

harenosus, Latin for sandy). Harenodynamics encompasses the dynamics of flow, boundary layer formation, and pressure, temperature, and gas (O_2) release conditions in the boundary layer, at high speed flow of sand along harenodynamic brakes. The LSL's most critical component is its braking assembly, particularly the linings. It is desirable to manufacture the linings on the Moon from lunar materials. A harenomechanical and harenothermodynamic data base must be established to define target characteristics.

The lunar environment provides many advantages for slide landing. Vacuum permits high-speed LSL approach without temporary communication blackout due to ionized boundary layer formation. The absence of atmospheric effects, and superb sky and ground visibility (including optical signals at night) permit high predictability and automation of approach navigation. The LSL body as a whole is not subject to aerodynamic heating, which probably simplifies the design and results in lower structural mass. Possibilities for aborting the landing exist practically to touchdown.

The LSL descends from low CLO along an elliptic path. For elliptic descent from 10, 20, and 40 km, the supercircular velocity excess at perilune is about 5, 10, and 20 m/s. Therefore, a retromaneuver of only a few meters per second reduces the speed to subcircular and causes the LSL to approach the surface at a shallow downward path angle.

The approach phase is followed by a supporting vertical thrust phase, whose purpose is threefold: control of the touchdown point; fine adustment of the vertical velocity component for smooth touchdown; and initial support of most of the lander weight, to control deceleration and stability during the high-velocity phase.

The vertical thrust, which replaces the aerodynamic lift of a landing aircraft, is eventually terminated in the third and final phase. The slide time is about two minutes, of which supporting thrust is needed for at most 90 seconds. Average LSL weight during this period is about 0.8 of its full weight due to the centrifugal effect during the high-speed phase. The supporting thrust of the LSL at 16 tons full lunar weight requires, under these conditions, a propellant consumption equivalent to a velocity change of less than 120 m/s—much less than the almost 1700 m/s that must be eliminated at conventional landing. LSL propellant consumption is therefore reduced to less than 10% of that required for conventional landing, corresponding to a hydrogen expenditure per unit mass of payload of $P_H \sim 0.01$.

Figure 6 shows one of my LSL concepts. A very controlled touchdown begins with the aft edge which, together with the supporting thrust, stabilizes the vehicle for careful ground contact of the main drag vanes. These are spring supported, inclined, and in adjustable yaw position, in order to hurl the lunar material away from the vehicle.

I have examined a multitude of other aspects for the slide landing process—navigational, harenodynamic, emergency options, *etc.* Suffice it to say that none appears to pose serious problems.

The Partially Enclosed Launch Track

For takeoff and transporting cargo from the Moon, I have considered alternatives ranging from Apollo I conventional takeoff to electromagnetic takeoff. The latter requires

Figure 6. Touching down at 5500 km/h after descending from circumlunar orbit to the Moon, the O_2/H_2 Lunar Slide Lander transfers its momentum to the surface materials and requires very little propellant to land. This concept will involve a small fraction of the H_2 needed for landing by conventional methods, rendering lunar access an affordable matter of routine.

a very extensive launch structure, very high g loads, and an enormous power input of the order of millions of kilowatt seconds during the acceleration phase. I propose instead a Partially Enclosed Launch Track (PELT), employing a chemical catapult concept that accelerates the LSL and freight to ascent speed.

Growth of exports is the bottom line of the lunar industrial economy. Ascent loads must eventually exceed descent loads by a widening margin. But also, for lunar self-sufficiency, resources such as hydrogen and water must be maximized at every opportunity. Therefore, the point of the PELT concept is not only to gain an economical lunar ascent capability, but to recycle the water and hydrogen from exhaust materials generated during lunar ascent. The concept also helps preserve the lunar vacuum.

The 12.4-mile-long facility comprises the launch tracks, payload platform, O_2/H_2 booster (catapult) and external data platform. The latter, which is linked to the booster, is located outside to provide more space for odd-shaped payloads inside the PELT.

The LSL and cargo mount on the payload platform. The platform runs on frictionless magnetic cushions to prevent material contact. The tracks are mounted on a small tubular enclosure that contains the chemical booster having four or less engines. The booster

is connected to the payload platform by a dorsal fin that fits through a slot in the top of the tubular enclosure. As the booster accelerates the payload to release speed, the slot is closed magnetically behind the fin, preventing escape of exhaust gases.

To catapult a payload toward a slightly eliptical orbit, which is then circularized for payload rendezvous with the CLSS, the PELT's booster reaches a release speed of about 1750 m/s (about 6800 ft/s). The exhaust velocity is over 4000 m/s. (*De facto* specific impulse is of the order of 30,000 to 40,000 seconds, which could be matched only by a very advanced nuclear pulse or mirror fusion system.)

After payload release, the booster is slowed down and retrieved. Meanwhile its exhaust water (with the hydrogen excess, if any, burned by oxygen injection behind the nozzles) has been automatically collecting at the back of the tube. Here it can be easily condensed by cold oxygen. If a 40-ton payload had been launched, about 7 tons of water would have been produced. It can either be used as water, in which case the propellant performs double duty, or it can be electrolytically separated into O_2 and H_2 for reuse as propellant.

One may assume an initial phase where the LSL returns to orbit as cargo carrier with high launch acceleration from a relatively short and simple Enclosed Launch Track (ELT). Figure 7 shows the ELT interior as an LSL is launched. The still light personnel traffic is handled by conventional vertical landing and takeoff. When the PELT is built,

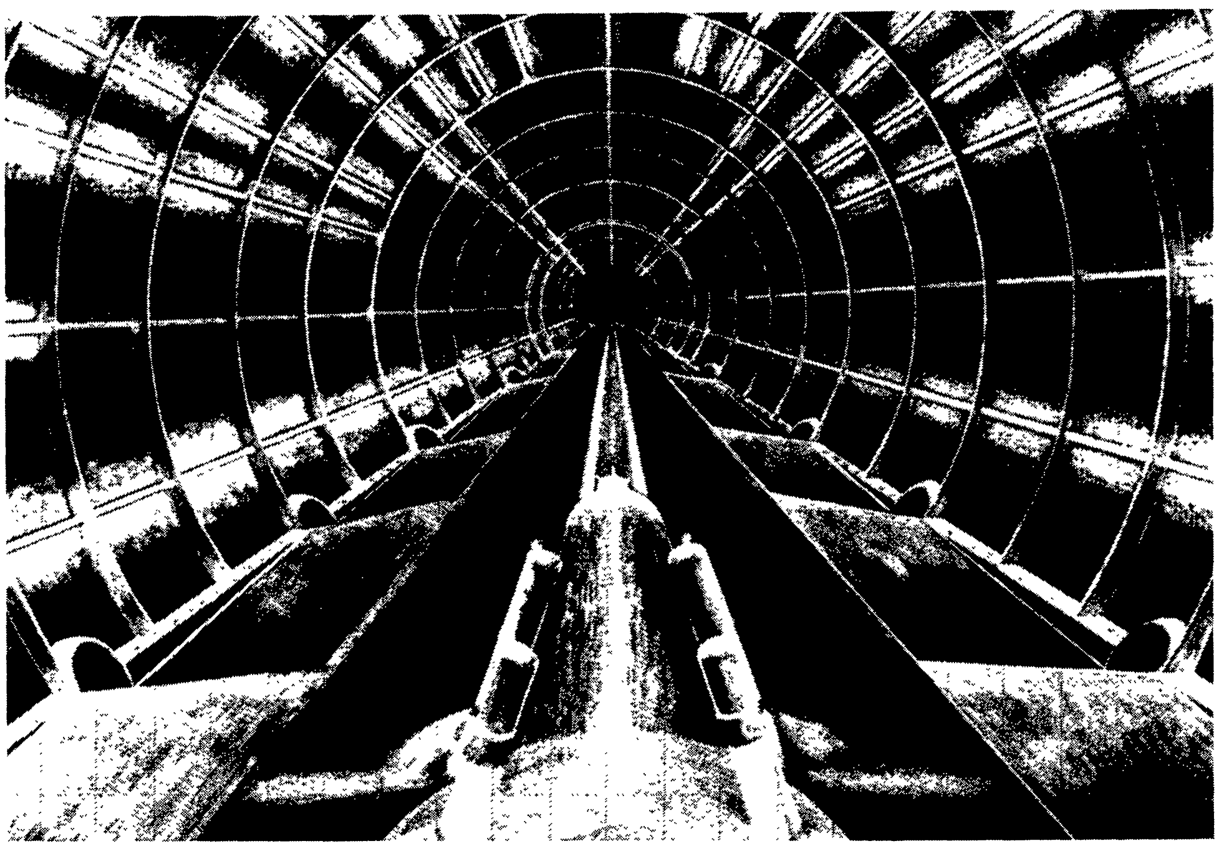

Figure 7. The Enclosed Launch Track accelerates a cargo-carrying Lunar Slide Lander to ascent speed, catapulting the vehicle into the trajectory for rendezvous with the Circumlunar Space Station.

it can grow in length, permitting progressively lower acceleration levels down to values suitable for acceleration-sensitive cargo and personnel. The PELT will eventually become a track for electromagnetic propulsion, once sufficiently high power levels are available to release about 60 million kWh in three minutes.

ELT and PELT construction will be greatly facilitated by the use of local materials and extensive automation.

THE EXTRATERRESTRIAL IMPERATIVE AND THE OPEN WORLD

The extraterrestrial imperative facing the human species was outlined in a paper that I presented in 1972: "Overshadowed by the limitations of the terrestrial environment, the scenario of world development will undergo fundamental changes in the next 30 years. But the need for resources will continue to grow. Therefore, the emphasis on opening new environments to industrial operations will grow. Since environments that are removed from our biosphere answer both the need for continued industrial growth and for reducing the industrial burden on the biosphere, the opening of extraterrestrial environments will become increasingly attractive, commensurate with economic viability.

"Thus, one of the fundamental changes in the world development scenario will be the transition from the classic closed-world to an open-world development model. The open world adds open-space and lunar-type environments to the terrestrial environment. The nearest of the second group is our Moon." The conclusions of the 1972 paper remain unchanged. They were adopted after the "limits to growth" precepts gradually became recognized as falsehoods.

In the past, human growth could unfold in a monoglobal framework. In the future, human civilization needs to be polyglobal. The Moon is the first step. It is a seventh continent, almost as large as the Americas. It is large enough to support a civilization. It alone offers the opportunity to create a strong exo-industrial economy based on highly advanced nuclear, cybernetic, and material processing technologies, ultimately turning large parts of the once-barren lunar surface into a lush oasis of life, capable eventually of exporting even foodstuffs to orbiting installations, if not to Earth (Fig. 8).

In an open world, there are no limits to growth—only to mindless multiplication.

THREE-DIMENSIONAL CIVILIZATION

For Selenians, creation will be the major trade. The human being and its technosphere arrive first and then create a biosphere. This kind of creation will require an approach that is rational and effective without precedent. It will require an intensive learning process, particularly for a life form that also possesses extraordinarily destructive tendencies.

In their modularized, adaptive, growing bio-niches, Selenian societies can develop a plurality of life-styles and new social structures. Whatever the details of the human relationships may be, Selenians will be space "amphibians" traveling with ease between surface and orbital gravities and later, in the gravities of Mars, as well as on the moons of Jupiter or Saturn.

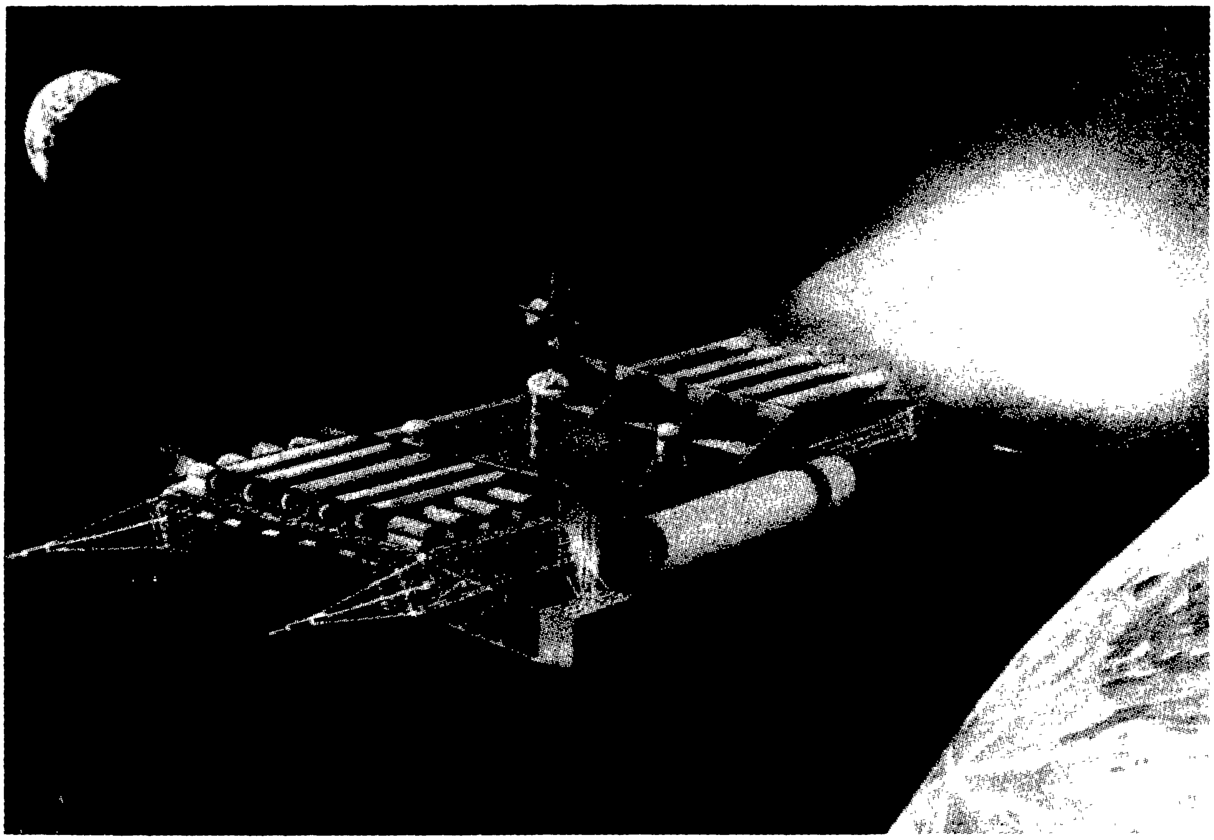

Figure 8. A cislunar superfreighter, powered by lunar oxygen and aluminum powder, carries lunar bounty produced by Selenians for their terrestrial customers.

For those coming generations who are born on the Moon and who are not transfixed by the beauties of Earth, and for those who remain on the Moon except for vacation or business trips to Earth, there will be no place in geolunar space more beautiful, vital, or abundant with the future than the Moon and the selenosphere created on it.

The Moon is a cause and a consequence. It offers even more than important contributions to overcoming our critical problems and achieving the essential technological advances. Selenopolis, symbol of a civilized Moon, is a new beginning of such magnitude that it can be compared only with man's emergence from the shady shelter of forests into the light of the open savannas.

The Moon is the touchstone of the human future. Instead of searching for and speculating about life elsewhere, we will put it there. Forthwith, civilization will be three-dimensional, and life will be polyglobal. Living at the ethereal shores of heliocentric space, the Selenians will be the Cosmopolynesians of the solar system, navigating between worlds. They will build the bridge between a dim past under terrestrial skies, where the great legends of human emergence tower, and a deathless civilization in a stellar future whose shadows beckon and long to be given substance.

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RAWLINGS '85