LUNAR SUBSURFACE ARCHITECTURE ENHANCED BY ARTIFICIAL BIOSPHERE CONCEPTS

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The integration of artificial biosphere technology with subselene architecture can create a life-enhancing, productive habitat that is safe from solar radiation and extreme temperature fluctuations while maximizing resources brought from Earth and derived from lunar regolith. In the short term, the resulting biotectural (biospheric and architectural) designs will not only make the structures more habitable, productive, and manageable, but will ultimately provide the self-sufficiency factors necessary for the mature lunar settlement. From a long-term perspective, this biotecture approach to astronautics and extraterrestrial development (1) helps reduce mass lift requirements, (2) contributes to habitat self-sufficiency, and (3) actualizes at least one philosophy of solar system exploration, which is to exploit nonterrestrial resources in an effort to conserve our natural resources on this planet.

INTRODUCTION

This study does not propose the viability of a completely self-sufficient lunar habitat any time in the near future, but it does recommend that the initial design stages take artificial biosphere concepts into consideration. The implementation of these regenerative technologies into the proposed subselene habitat scheme may be more costly initially, but the costs of long-term operation will be reduced as the area of the facility expands to accommodate the regenerative artificial biosphere systems (*Hypes,* 1988).

BIOSPHERICS, THE BIOSPHERE, AND ARTIFICIAL BIOSPHERES

Biospherics has been defined as an "integrative science of the life sciences just as astronautics is an integrative science of the physical sciences. Together with astronautics, biospherics opens up the ecotechnical possibilities to expand life on Earth into other parts of our solar system" (*Allen and Nelson,* 1986).

Earth's biosphere, which is the layer of life on the surface of the planet inclusive of the atmosphere, is the only presently known biosphere. This planetary-wide system has been continually present on Earth for over 3.5 b.y. and is the primary geologic force maintaining the transitory balance between the gaseous, solid, and liquid matter of the planet. The biosphere supplies most of the free energy that fuels humans (with the air they breathe and the food they eat) and their machinery. Whenever humans venture beyond Earth's biosphere into space, they must always take some form of the biosphere with them in order to survive, be it containerized food, oxygen, or fuel. There is an intrinsic connection between humans and the Earth's biosphere that becomes more and more apparent the further "disconnected" or away from Earth we get. Space travelers need food, water, an adequate atmosphere, and a protective, psychologically suitable shelter. Limited by such things as rocket payload lift capability, economics, and an incomplete understanding of the biosphere's mechanisms, the challenge is to design an evolving habitable environment that will provide these necessities for continually longer periods of time with fewer and fewer resupply missions.

Useful human habitation of the Moon will require environmental conditions similar to those on Earth where humans evolved. Like the biosphere of planet Earth, lunar habitats as artificial biospheres should strive to be stable, complex, evolving systems containing life, composed of various "scaled-down" ecosystems operating in synergetic equilibrium, essentially closed to material input or output, and open to energy and informational exchanges. As we have yet to create a livable artificial biosphere, achieving this goal will not come in the first phase of lunar base development, or perhaps not even in the second or third phase. However, applying what we know in the initial stages will only expedite the growth of our first lunar "hut" into a life-promoting artifical biosphere habitat just as the Earth's biosphere evolved from a once barren planet.

A TUNNELING SCHEME FOR A LUNAR BASE

A first-stage lunar base can be created using a tunneling device that produces an underground network of habitats, work spaces, and passageways. The resulting interior walls of the tunneled chambers are hardened silica to which inflatable membranes can be attached and deployed creating the desired environment. These habitats will be essentially isolated from the lunar surface environment by a closed structure composed of components derived from the lunar surface itself and an inflatable interior bladder. The scheme also provides a practical way to create the large amounts of pressurized volume needs for the regenerative life support of a large lunar habitat. The basis for building subselene facilities are (1) protection from radiation and meteorites, and (2) a relatively constant temperature of a -20°C, which exists at depths of 3 m below the lunar surface.

Background

Current thinking on the initial lunar base configuration is exemplified by *Kaplicky and Nixon* (1985) in which a prefabricated module is built on Earth, launched into low Earth orbit, then transported to the lunar surface. At this point the module will be soft landed on the surface and then covered with regolith to protect the inhabitants from harmful solar and cosmic radiation. The modules could be existing space station designs and outfitted with much the same hardware.

The application of this logical scenario for an initial lunar base configuration would advance the knowledge of human productivity and technology interfaces in a foreign environment. In the meantime, testbed habitats conducted in Antarctica, underwater, and in other harsh and isolated environments are furthering this understanding. Based upon this current thinking, we can examine an alternative scenario facilitating mankind's expansion to the Moon.

A proposed cost-effective method for an alternative next phase lunar base using indigenous materials could be achieved by using a thermal tunneling device (*Rowley and Neudecker,* 1985) and an inflatable membrane configured for specific uses. As seen in previous studies of lunar habitats, most involve heavy manufacturing of components and modules. These systems need to be launched from Earth, placed in lunar orbit, and then deployed on the surface. It would seem reasonable to use existing lunar materials to create the shell of these habitats, thus reducing the cost of the heaviest component by using material that is indigenous to the lunar environment. This system also holds potential as a way to enclose the large amounts of pressurized volume required for Controlled Ecological Life Support System (CELSS)/ biosphere applications.

As we have seen throughout architectural/construction history, humans have always used materials and processes that were indigenous to the local region. From the use of ice for igloos in Alaska, bamboo and grass for habitats in jungles, and sod and adobe during the expansion into the American West, people have adapted their resources, knowledge, economics, and creativity to serve their needs. Practical designs for space facilities are derived from that same context of creativity and resourcefulness. The use of indigenous lunar materials could eliminate a major cost while providing a shielded habitat.

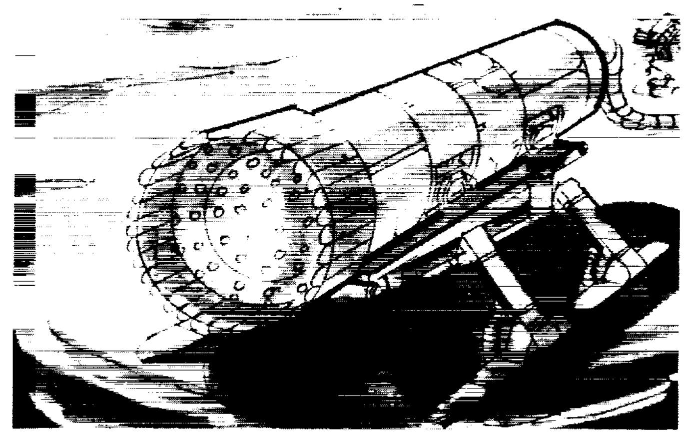

Fig. 1. The melt-tunneler separates from the systems tractor.

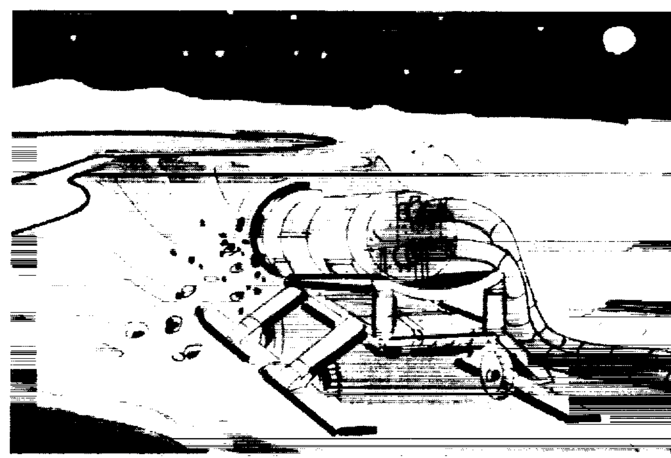

Fig. 2. The device is activated and begins to core.

Subsurface Scenario

A device called a subselene nuclear powered melt tunneler was presented in 1985 by J. W. Neudecker and J. C. Rowley (*Rowley and Neudecker,* 1985). This concept used heat from a nuclear reactor to melt rock and form a self-supporting, glass-lined tunnel. They favored subselene tunneling for the following reasons: (1) the process uses highly energy efficient nuclear power supply, (2) it does not require water or other rare volatiles for open system residue handling or cooling, (3) the mechanism can penetrate through a varied sequence of rock types without complicated configurational changes, (4) the process forms its own support structure as it goes along, and (5) the system is highly adaptable to automated operation.

This type of mechanism can be launched into orbit with an expendable rocket system. The unit would proceed to a low lunar orbit, deploy the protective transportation shields, and begin its descent to a predesignated site on the Moon's surface. After soft landing, the tunneling device detaches from the support tractor containing the main guidance computer, Earth communication system, and regolith extraction pumps (Fig. 1). Then the tunneling device manuevers into position, attains the required angle, and ignites (Fig. 2). Once there is a cavity, the device attaches its gripping pads to the sides of the newly formed tunnel and continues digging in a preprogrammed configuration, be it linear, circular, or octagonal (Figs. 3 and 4).

After the inner walls of the tunnel have cooled down sufficiently, astronaut construction crews would arrive and install the inflatable interior membranes, which are transportable in a compacted form (Figs. 5 and 6). These membranes would provide a secondary pressure skin should the fused glass walls of the tunnel crack or lose pressure integrity. Membranes previously researched by *Goodyear Aerospace Corporation* (1982) were expandable, flexible structures with enough rigidity to infill the interiors of the tunneled sections. They could be easily attached to the hard silica walls and expanded.

These inflatable units would be predesigned and outfitted according to their desired uses. Each module could be 40 ft in length and 12 ft high at the center point of the barrel vault featuring ready-made interior partitions and circulation corridors. Ducts and tubes would already be in place within the framework composition of the inflatable material.

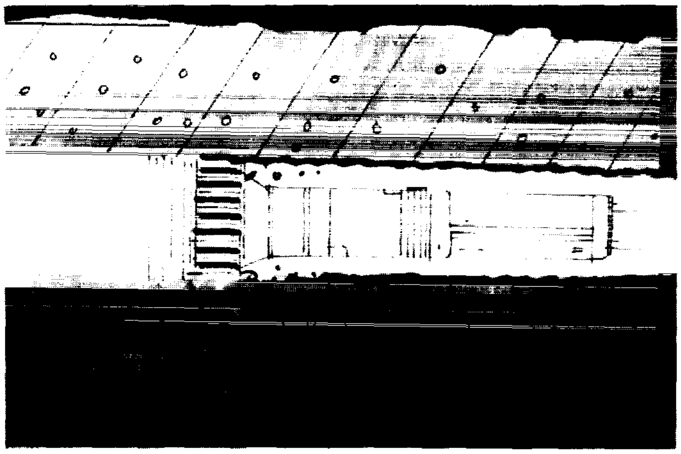

Fig. 3. Subselene chambers are created.

Fig. 5. Astronauts land with interiors.

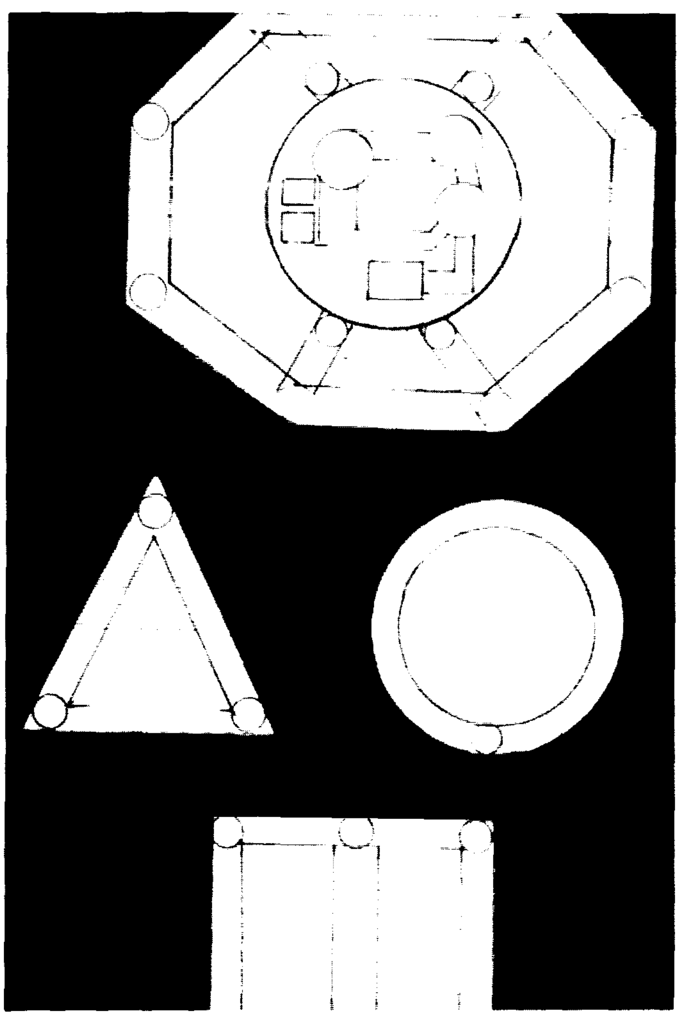

Fig. 4. Preprogrammed configurations of tunneler paths.

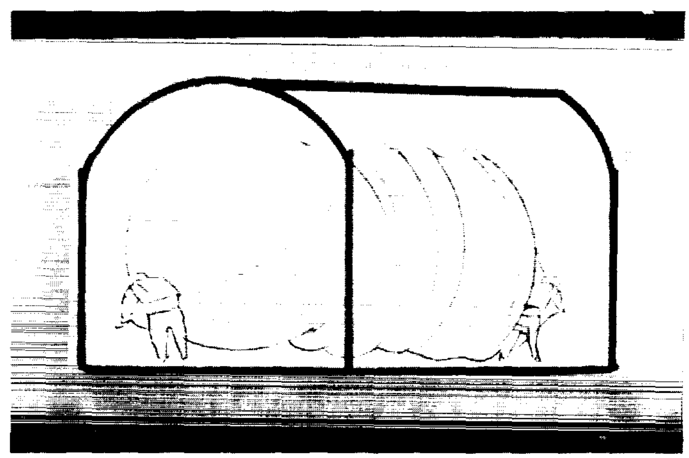

Fig. 6. Install inflatable interiors safe from surface radiation.

Each module can be connected to another module with 12-ft-diameter interlink node providing an entry/exit airlock to the exterior environment. The interlink nodes are also suitable as emergency rescue pods when providing access to the surface. Similiar nodes are being considered for use in the space station. Modules and nodes could also be pressurized for use as artificial biosphere chambers (Fig. 7).

Large volumes designated for artifical biosphere applications, perhaps on the order of thousands of square feet, may not require the extra security the inflatable interior offers if the volmes were not inhabitated on a day-to-day basis. The glass-walled tunnels themselves could be sealed off into large pressurized growing chambers. Interiors could then be attached to the mechanical equipment or the life support system.

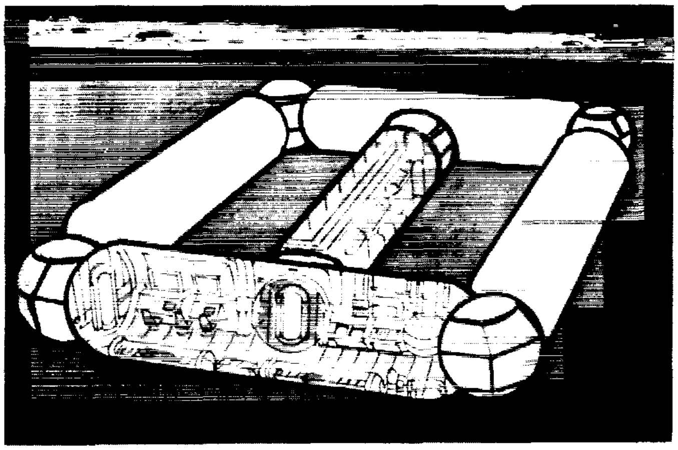

Fig. 7. Modules can be previously outfitted for labs, growing areas, or habitats.

This subselene scenario presents alternative architectural and construction processes that are compatible with plans to integrate CELSS or artificial biosphere technology into lunar habitats. The proposed scenario features the following:

Minimum surface time. The hazardous radiation astronauts are exposed to during extravehicular activity (EVA) construction can be reduced.

A balance of manned and automated technology. Surface construction tasks that subject humans to hazardous solar radiation could be accomplished by the use of automated subselene systems.

The following construction and operational tasks requiring the presence of humans can be conducted for the most part in the resulting, protected subselene conditions.

Expendable launching system. Expendable launching systems are viable options for deployment of the tunneling device. Transportation and delivery of lunar excavating equipment and other automated systems can economically occur before manned flights are launched.

Earth-based analogs. Tunneling and construction in harsh and isolated environments such as Antarctica and underwater continue to provide valuable information relevant to this subselene scenario.

Economical creation of pressurized volumes. Elimination of heavy material support from Earth could allow a mature lunar settlement to achieve self-sufficiency by the creation of adequate habitation area and the required large volume necessary to implement a biospheric life support system.

A minimum facility volume required to merely feed a hypothetical crew of six lunar astronauts can be calculated. Data from Martin Marietta indicate that one hypothetical lunar base crew member requires 1.36 lb of food per day (*Hypes*, 1988). A Phytofarm hydroponic facility in Illinois is currently producing 1 lb of food per day for every 25 sq ft of the facility (*Field*, 1988). Calculations from this data indicate that every crew member requires 34 sq ft of growing space to meet the 1.36 lb of food per day. A six-member crew would therefore require approximately a one-story, 204-sq-ft hydroponic facility. As the Phytofarm facility is a large-scale operation, a contingency factor for the minimum volume of support systems required to produce a certain amount of biomass comes into play in this calculation. Since the melt tunneling technology can evacuate subterranean sections up to 15 ft wide, an intensive hydroponic facility only 12 ft long would provide the necessary volume needed for supplying food.

INTEGRATION OF ARTIFICIAL BIOSPHERE CONCEPTS

The Earth's biosphere did not happen overnight but grew from a sterile world to an evolving, complex living entity. Over its approximately 3.5-b.y. lifetime, the Earth's biosphere seems to have maintained an optimal, evolving state of health. Health could be defined as the state of dynamic equilibrium between the organism and its environment, which is a definition that could be appropriately applied to a successful biosphere-oriented lunar habitat and its inhabitants. Designing, constructing, and maintaining a healthy habitat that can supply itself with life essentials such as food, water, and air is a challenging task akin to raising a child that will someday walk out the door and live its own life. The process must grow and evolve just as the young child or the young lunar base. The habitat should be designed to accommodate growth from the very beginning.

There are many artificial biosphere concepts that could be integrated in even the earliest stages of a lunar base. These include everything from applicable wilderness survival techniques (*Dowling et al.*, 1988) to the current space station reference configuration Environmental Control and Life Support System (ECLSS) featuring water reclamation and oxygen recovery subsystems (*Hypes*, 1988). For example, the Phytofarm hydroponic process makes efficient use of water by recirculating the nutrient solution—nitrogen, phosphorus, potassium—and using just enough for the plants to absorb their fill (*Field*, 1988). By controlling the environmental conditions of temperature, humidity, and light by computer as well as the input of carbon dioxide stored in tanks, an optimum rate of photosynthesis could be achieved in a similar hydroponic system on the Moon.

The Role of Proper Plant Combinations

Simple algae and bacterial colonies could be included for immediate operation in a first-stage lunar base to supply certain functions such as waste-recycling, gas exchange, food production, and eventually fertilizer. These algae and bacterial elements could be employed in the agricultural system and their by-products stored for later use. Empty descent propellant tanks are suitable for storage or cultivation tanks providing they can be completely cleaned of harmful residue. Small greenhouses and water tanks could also be made from simple, low-pressure inflatable structures of plastics or thin foil material.

One resourceful aspect of maximizing biospheric processes in space development concerns the notion of transportability. Lifting heavy materials into orbit is a costly and energy intensive process. However, many useful materials and functions can be generated by carrying just a mere seed or a single cell into orbit. One example is bamboo, which has been used for centuries as a fundamental building component on Earth for both housing and furniture. Bamboo could also be grown and used on the Moon, eliminating the high cost of transporting certain basic building materials. One can cheaply transport bamboo seeds to the Moon, cultivate them in lunar soil, and then use the mature plants to construct everything from furniture to equipment racks.

Other key ingredients to this synergetic combination of plant materials beside algae and bamboo would be the foodstuff plants such as spinach, lettuce, corn, and beans. Under artificial conditions, spinach, for example, can be germinated in just one day as compared to the standard eight days. Under the same conditions, lettuce can grow from seed to full head in 26 days (the best lettuce can do outdoors in soil is 42 to 60 days). At normal atmospheric CO_2 levels (340 mg L-1), plants like corn most efficiently fix CO_2, while at elevated CO_2 levels (1200 mg L-1), plants like beans would have the advantage in CO_2 fixation due to reduced carbon loss via photorespiration (*Beer,* 1986). Soybeans also offer an optimal protein source since the biomass and volume required to raise beef or foul is unquestionable in the near-term lunar base.

Just as a plant is a system that processes earth and atmosphere, so can plants under the right artifical conditions process properly conditioned lunar regolith or nutrient-enhanced water, generating many useful products and by-products with a high degree of recyclability. It is foreseeable that the obvious improvements in technology and cultivation techniques can make the use of bioregenerative systems competitive with other life support systems, especially with increased numbers of crew and durations of stay at a lunar base.

Architectural Components

As the design for the proposed subselene facility matures, so do certain concepts currently in development. The Biosphere II Project in Arizona is a private project under development by Space Biospheres Ventures exploring the issues of artificial biospheres. This 98,000-sq-ft structure is designed to be a materially closed and energetically and informationally open system capable of supporting six to eight people (*Hawes et al.,* 1988). The research being done at Biosphere II includes many applications to lunar base design and to the proposed subselene scenario.

One of these applications is the "lung" or pressure/volume compensating chamber. Since the subsurface lunar facility will be completely sealed, an expandable lung device accommodates changes in the facility's internal air volume and eliminates pressure fluctuations that could break the seals and leak the valuable atmospheric elements. The variable volume chamber expands and contracts with shifts in the internal atmospheric volume-caused changes in temperature and pressure.

Achieving a total seal between the subselene structure's internal bladder and the access nodes is critical. The sealing techniques currently being researched must withstand temperature variations, and terrestrial ones are not as extreme as the temperature variations structures on the lunar surface will be subject to.

Advanced sensor technology and artificial intelligence systems will control such environmental parameters as light intensity, temperature, soil moisture, relative humidity, CO_2 and O_2 concentrations. Certain indicator plants can also assist in monitoring such key health vectors as pH and trace contaminants.

The use of a tiered facility structure could also assist natural convection currents to move moisture and temperature to and from designated interior spaces. A multimodule facility can be designed with each module at a different level so that warm, moist air flows toward the agricultural module and cool, dry air flows toward the module containing heat-producing equipment. The chambers could optionally be sealed off from each other and operate as temporary independent systems in emergencies.

The beneficial use of solar radiation is very important from the standpoint of artificial biosphere technology and subselene architecture. If the lunar facility is located near the lunar pole, solar radiation may prove to be near constant and harnessable with one or two strategically placed collector towers (*Dowling et al.,* 1988). If not, the 14 day/14 night cycles on the Moon make solar radiation impractical as an energy source unless an alternative system such as double lunetta system is used (*Ehricke,* 1980). These large, orbiting reflectors may be positioned in orbit so that sunlight is continuously reflected onto the area surrounding the lunar base (Fig. 8). The sunlight can then be harnessed in a variety of means, including solar collectors, and brought down inside the subselene facility with fiber optics.

Fiber optics reduce the need for transporting lamp systems and decrease the power requirement. Proper adjustment of a fresnel lens onto a solar optic collector can filter out harmful ultraviolet and photosynthetically ineffective infrared rays. Such solar optic systems with a lunetta tracking system could provide the lunar habitat with the life-giving properties of light minus the harmful ultraviolet elements. The sunlight could be brought from above ground and down into the subsurface facility. The application of solar optics to CELSS and subsurface lunar habitats are many. They include (1) cultivating algae-like chlorella in sealed tanks as a promising source of food and gas exchange, (2) intensive horticulture and aquaculture processes, (3) purifying and recycling human waste, and (4) satisfying the need humans have for sunlight both physically and psychologically (*Mori,* 1988).

SUMMARY REMARKS

If humans are to someday become self-sufficient on the lunar surface, the planning, design, and implementation of the life-supporting habitat must begin in the first stages. As the viability of a completely regenerative system has yet to be proven, the design should implement the currently practical aspects of artificial biospheres with a plan for expansion.

The proposed subselene tunneling system is able to create areas safe from solar radiation and extreme temperature variations.

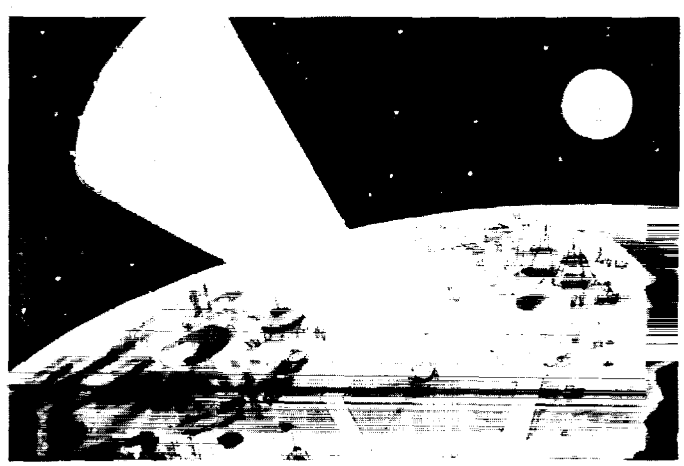

Fig. 8. Lunetta reflecting sunlight into subselene fiber optics system.

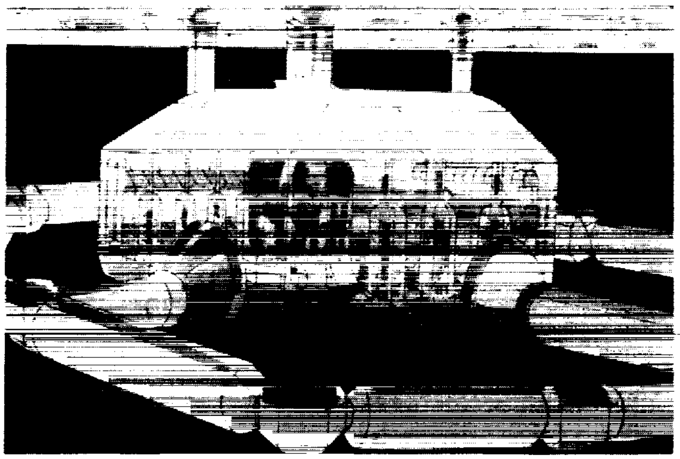

Fig. 9. A subselene growing chamber of an advanced lunar facility.

Augmented with artificial biosphere concepts, these subselene modules can become more habitable, productive, and continually less dependent on resupply as progress is made. Many of these subselene module cavities can work together to create large pressurized volumes, which are ultimately necessary for a more self-sufficient, artificial biosphere (Fig. 9). The objective should be to design a system that will be functional in the short term while maintaining the flexibility to evolve into a mature, independent lunar facility.

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