Design and Construction for Self-sufficiency in a Lunar Colony

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ABSTRACT

Construction on the moon poses radically new design challenges. We will give a brief overview over the resources available, the structural loads and other design requirements, and some suggestions for construction approaches. The main structural load will not be gravitational loads, but rather internal pressure and airtightness, while additional specific considerations such as radiation protection and meteorite impact safety must be considered. It is argued that any long-term habitat on the moon will be buried deep – either by piling regolith on the structures or beneath rock in caves or mineshafts.

BACKGROUND

The recent decision by the US president to send Americans to Mars while establishing "an extended human presence" on the moon has sparked an interest in space bases and space travel that surpasses anything since the six moon landings 1969-1972. Note, however, that there are still no concrete plans for a permanent lunar settlement, and the planned trip to Mars can be viewed as a purely flag-and-footprints mission. In the present paper, we will discuss construction issues for a somewhat more ambitious, self-sufficient moon-base. We will assume that the base will be designed and built for sustained habitation by humans, thus prohibiting any bulk imports from Earth for transport cost reasons.

The moon has fascinated humans in all times, and there are numerous stories about voyages to the moon. Already in 1959, the US army had concrete plans for a lunar base. The Apollo project, that led to the first Moon landing in 1969 involved more than 400,000 people in 20,000 companies, but after 12 men returned with less than 400 kg Moon rocks and dust, the interest waned. However, Lunar explorer, SMART-1 and many recent books (e.g. Schrunk et al. 1999, Eckart 2000, and Koelle 2001) bear witness of a growing interest today. Most studies concerning long term exploration of space and celestial bodies mention in-situ resource utilisation (ISRU) and raw material supply from the Moon. An important requirement for lunar production will be to minimise supply transport from Earth. This would be achieved efficiently by a self-sufficient colony on the Moon. A Moon Colony would also secure a foothold in Space for humanity, and protect the exploration of at least the Moon from the effect of future space budget cuts.

Interestingly, the requirements for a lunar colony coincide to a large extent with requirements on any human community. In particular, the same approach can be valuable to get better control over the environmental impact of its activities and increased robustness with regards to extreme events such as terrorism or natural disasters.

ENVIRONMENT AND RESOURCES

In any given community, the cost and availability of resources is dependent on local mineral sources and the cost of trade and transport to bring in resources from other communities. Since this cost is varying with time and the political climate, it is illustrative to consider a community in complete isolation. Also, because it will be difficult to clear the mind and imagine a terrestrial community as being completely isolated, the extreme case of a colony on the moon can be considered an illustrative example for further elaboration and application to terrestrial problems.

Table 1: Lunar soil composition (weight %, from Blair 1998 [1] and Prado 1998 [2])

Element	**Highland**	**Mare**	**Earth**	**Earth rank**	**Applications**
Oxygen[1]	45	42	47	1	Fuel, essential air constituent
Silicon[1]	21	21	28	2	Glasses, ceramics, etc. Solar cells.
Aluminium[1]	13	7.0	8.1	3	Electric wire, structures, mirrors
Calcium[1]	11	7.9	3.6	5	Ceramics, electrical conductor
Iron[1]	4.9	13	5.0	4	Structural steel
Magnesium[1]	4.6	5.8	2.1	8	Metal alloying element
Sodium[1]	0.31	0.29	2.8	6	Chemical processing, Plant nutrient
Titanium[1]	0.31	3.1	0.44	9	High strength metal
Chromium[1]	0.085	0.26	0.01	21	Metal alloying element
Potassium[1]	0.08	0.11	2.6	7	Chemical processing, Plant nutrient
Manganese[1]	0.068	0.17	0.095	12	Metal alloying element
Phosphorus[1]	0.05	0.066	0.11	11	Plant nutrient
Sulphur[2]		0.12			Chemical processing
Carbon[2]		0.015		17	Life, chemical processing
Nitrogen[2]		0.008			Plant nutrient, air constituent
Hydrogen[2]		0.006		10	Fuel, water, chemical processing
Helium[2]		0.005			Inert gas

The Moon is lacking the most important survival component: a breathable atmosphere. But strange as it may sound, oxygen supply will not be a problem for the Moon colonists. The lunar soil (actually more like a fine dust, usually referred to as regolith) actually contains more than 40% oxygen that can be extracted by simple processes (actually, large quantities of oxygen will form as a by-product of many mineral enrichment processes that will be needed for other purposes). The lunar soil (see table 1) also contains high concentrations of silicon, aluminium, iron, magnesium and titanium, as well as smaller amounts of chromium, manganese and sulphur. These elements can be extracted and used for manufacture and construction materials. In addition, apart from lacking nitrogen the lunar soil is reasonably fertile, containing calcium, sodium, potassium and phosphorus in suitable amounts for nutrition of plants.

The primary resource deficit is that the essential light elements hydrogen, nitrogen and carbon only appears in trace amounts in lunar soil, as they do not form stable compounds and thus have escaped to the vacuum of space. However, according to Lunar Prospector, at the lunar poles there are elevated concentrations of hydrogen, corresponding to 300 million metric tons of water. The source of this hydrogen is probably icy comets, which means that there should also be large amounts of nitrogen and carbon in the form of ammoniac and methane ice. Energy is abundant, as no clouds or atmosphere restrict the sunlight. With appropriate placement of solar panels close to the lunar south pole, it will be possible to have almost continuous power supply, with shadow only during 10 hours out of the 708-hour lunar day and night.

SURVIVAL REQUIREMENTS

With the introduction of life cycle assessment practices, manufacturing optimisation has taken a step from sub-optimising in each step of the production chain towards a more globally optimal approach. We take this approach one step further, and aim for optimisation of the entire manufacturing system, as needed for human survival. Focusing on minimum use of energy and materials in a total sense, recyclability and refurbishment will be encouraged, leading to increasingly eco-efficient processes and designs.

The self-sufficiency approach will give a step improvement in knowledge management, by collecting and structuring resource usage information across a wide range of industrial processes required for modern society as a whole. A fundamentally new approach to production planning is suggested, that will naturally encourage collaboration and information sharing over many tiers of production, tying the production community much closer together in a knowledge network of sharing distributed information on material requirements and possibilities throughout human society. Product and process optimisation on a much wider scale will become possible, leading to significant global cost savings.

As a first step in the planning process, a structured breakdown of the human survival needs in terms of manufacturing requirements has been initiated. In a recent study (O'Handley 2000), financed by the NASA Institute for Advanced Concepts, the material requirements for a small self-sustainable Moon base was investigated. According to this study, the survival requirements per person are:

Food, oxygen and water produced in a closed ecological life support system (CELSS): 620 grams of food, 850 grams of oxygen and 28.75 litres of clean water per day. The limiting factor of these is food, requiring a cultivated area of 20 m^2 per person.

Pressurised volume: 1200 m^3, over an area of 200 m^2. The area is used for living area (50 m^2), agriculture and common areas (80 m^2), process equipment, manufacture and maintenance (50 m^2), and power, control, storage and miscellaneous (20 m^2).

Raw materials are obtained by heating and chemical treatment of lunar soil. An important limitation seems to be atmosphere losses through diffusion, leakage and air locks. For replacing the nitrogen content of 0.5 % daily atmospheric losses, it would be necessary to process more than 400 metric tons of lunar soil per person and day. Even if the observed hydrogen at the lunar poles were in the form of nitrogen rich cometary ices, more than 100 kg per person and day would still be necessary. However, with improved airtightness to 0.1 % daily losses, and if most nitrogen *losses* can be replaced with "cheaper" gases (such as oxygen), the regolith processing requirements would come down to a reasonable 1kg per person and day.

These survival requirements can be further traced into design parameters describing the material production system as required by a human community, as illustrated in figure 1. Note that this schematic requirements breakdown can be applied to any human community. Thus, this approach can be easily applied also to terrestrial applications such as disaster relief, establishing infrastructure in underdeveloped areas, and for resource management in modern manufacturing supply chain networks.

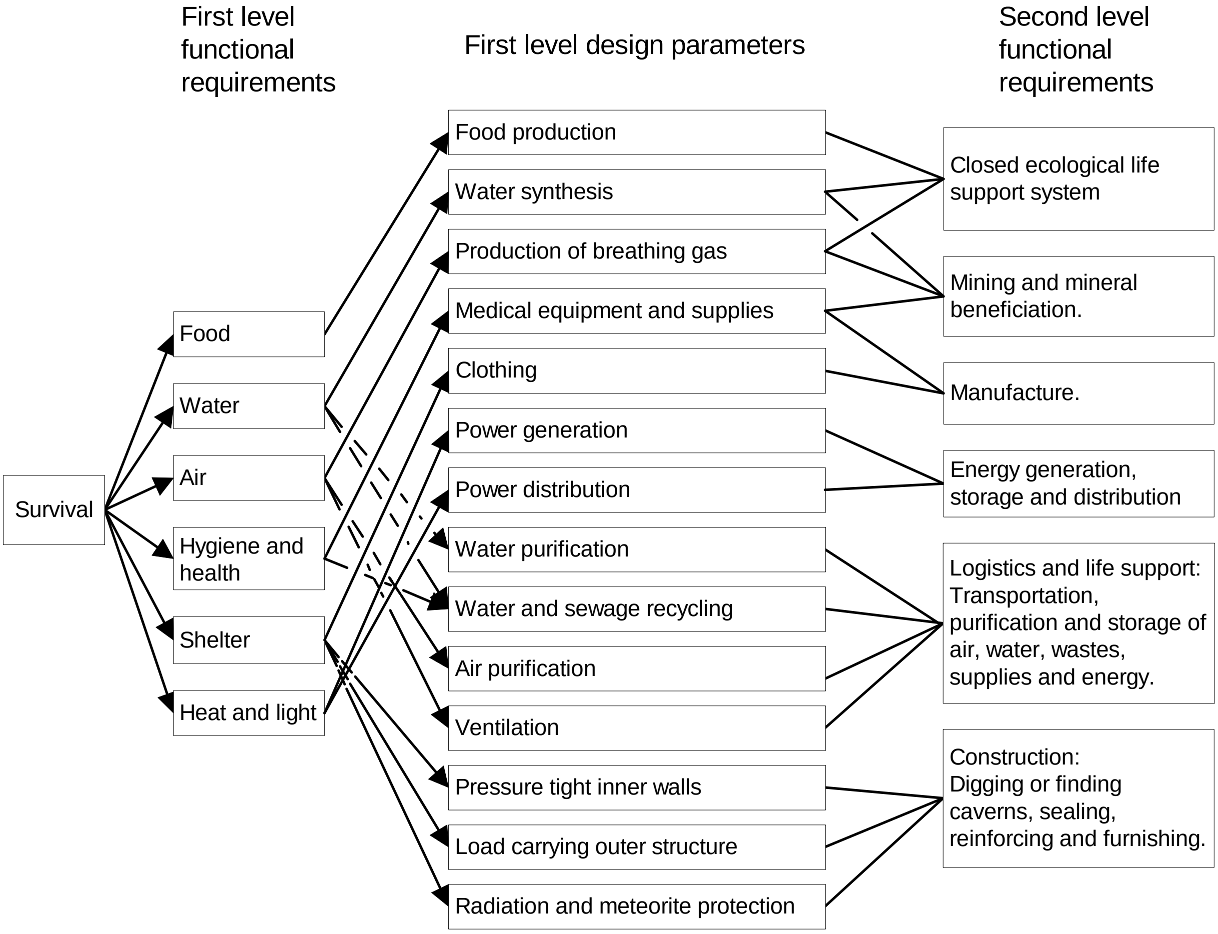

Figure 1: Survival requirement breakdown (Järvstråt, 2003)

DESIGN LOADS

The conditions prevailing on the Moon will result in important differences in loads acting on structures as compared to terrestrial structures. The lower gravity ($1/6^{th}$ of that on Earth) will drastically reduce the effect of structural weight as a design consideration, while other safety critical design issues will assume unparalleled proportions in the harsh lunar environment.

Gravitation

Perhaps the most obvious difference compared to terrestrial conditions is the lower gravitational loads ($\frac{1}{6}g$). In fact, this reduction will somehow be compensated with the additional weight of the shielding covering structures. Consider a roof structure at 500 kg/m^2. Weighing $0.5 \cdot 9.8 = 4.9$ kN/m^2 on the Earth, the same structure with 2m-regolith shielding of density 1500 kg/m^3 would on the Moon give a force of $(0.5 + 2 \cdot 1.5) \cdot \frac{1}{6} \cdot 9.8$ =5.7 kN/m^2. Thicker shielding would increase this downward load correspondingly. This means that, in general, there will not be a reduction in the vertical loads to parallel the reduction in gravitation.

Internal pressure

The biggest difference will come from the application of inside pressure. In a structure with inside pressure of one atmosphere, the uniformly distributed outward load will be very close to 100 kN/m^2, which corresponds to the gravitational load of almost 40 meters of regolith. Thus a structure will be almost under the same gravitational loads as on the Earth, but in addition a 20 times greater upward force will create tension in the vertical members. This will change the well-understood concept of column and result in the adoption of a new concept like “tension-compression-column”. Correspondingly, habitats will be pressure vessels more than “buildings” from a structural-integrity point of view.

Radiation

The moon does not have a protective magnetic field like the van Allen belt that shields the Earth from the bombardment of charged particles from the sun. And there is no atmosphere to keep electromagnetic radiation down. Thus, if genetic damage due to radiation is to be avoided, heavy shielding will be necessary. According to common estimates, about 2 meters of rock would provide sufficient shielding, also for rare events such as solar flares. If shelters can be provided and used during solar flares, the main body of the habitat may have significantly thinner shielding. However, such a design solution would force activities and/or comfort to be considerably reduced over extended periods of solar flares.

Meteorite impact and moonquakes

The moon is much less geologically active than Earth, being smaller and thus more solidified. Thus, moonquakes due to seismic activity will be a minor problem. The corresponding "load case" on the moon, that must be considered, is necessary the impact of a large meteorite. Note, however, that although the moon is pockmarked by an incredible number of meteorite impacts, large meteorites are very rare. Further, with proper radar surveillance, an advance warning would arrive with quite sufficient time to evacuate sensitive equipment and all personnel from threatened areas near the impact. Perhaps even to reduce air pressure or take other active damage attenuating actions.

Airtightness

As discussed in the section on survival requirements, above, the level of airtightness that is achieved will be a key parameter in determining the material supply necessary for sustaining the lunar colony. Thus, the treatment of seals and the choice of an airtight structure or an inner or outer sealing skin must be given careful consideration, and may well be one of the more demanding material challenges for the ISRU production engineers. Airlocks and seals between habitat sections and the external vacuum must also be designed to minimise air losses.

OTHER DESIGN CONSIDERATIONS

For any construction activity launched outside the gravity well of Earth, transport costs will completely dominate the budget, unless the highest degree of In-Situ Resource Utilisation (ISRU) is achieved. Thus, in preliminary design considerations for a long term solution, it is better to ***choose*** the requirement that all manufacturing equipment used shall be possible to manufacture within the production system (community) studied. The reason for this assumption is not a belief or a wish that this complete material isolation should be implemented, even for a lunar colony. The reason to enforce this conceptual isolation is to clear the mindset from the traditional thinking in supply and demand and long manufacturing routes and perform an optimisation from a societal utility point of view. It is also much easier and more straightforward to impose complete self-sufficiency than to decide á priori on a level of "essential" material supply. An obvious "solution" to self-sufficiency would be a return to middle age technology. However, an international consortium with 32 industrial and academic members is planning research efforts to deploy appropriate technology to maintain or even improve the standard of living, in the IMS project "Towards the Ultimate Self Sustainable Society - Modelling In-Situ Resource Utilisation for a Lunar Colony (Moon-ISRU)" (Järvstråt et. al. 2001). By mapping the resource flow from nature through the production chain to human use, not only will it be much easier to reduce environmental impact of society, but production facilities can be optimised for best economy in any given market situation. Consequently, the entire economy can be made much more robust, with lower vulnerability to fluctuations in markets and resource availability as well as to natural disasters and terrorism.

During the Middle Ages, trade routes were too uncertain to rely on for survival, and thus all communities had to have at least basic production capacity within reach. Since then, with increasingly safe and cheap trade routes, specialisation has become increasingly profitable resulting in small niche producers and multinational assembly giants, trading with others in similarly restricted specialisation goods. This specialisation has certainly given large benefits to humanity, but at the price of an ever increasing interdependency and strong reliance on the proper functioning of a large and diffuse network of production facilities all over the globe. Today, however, there are strong signs that the tide is returning towards short series and customised products. Taking this trend one step further, it should be possible to define the minimum production facility that will still be able to support a modern community.

Having defined the target of material self-sufficiency, the challenge is to design a fully self-contained production system that can support its workforce with as much surplus production capacity as possible. Or, equivalently, to design a production system that can supply a given number of people using as little workforce as possible, freeing the remainder of the community for other activities than keeping the society going.

This will require a reversal of the common trend towards highly specialised production with sophisticated half-fabricates. Instead, versatile production units, each capable of manufacturing a wide array of goods that are somehow “similar” and fits the same tier in the production chain will be required. Specifically, the lunar habitat construction process must be designed from a minimum set of building blocks and/or using highly flexible freeform production methods. If even the equipment used for construction can be manufactured on site, by inhabitants, using lunar produced materials and lunar produced manufacturing equipment, then the sustained cost for keeping and expanding the moon habitat will be close to zero for us Earthlings.

SETUP AND HABITAT TYPE SELECTION

When men will go to the Moon this time to stay, one of the basic concerns will be where to stay. Their first habitats will be their carriers, as it has been before during Apollo visits. But this time it is probable that they will have necessary material and equipment with them to erect prefabricated structures, either carried with the same vehicle or transported in another mission. It is probable that this structure will be obtained by extending or enlarging one of the cabins carried to the lunar surface. This additional structure may be constructed as an inflatable structure or a "tensile-integrity" (tensegric) structure to fulfil the requirements of having a lightweight structure. (Benaroya 1993, Sadeh & Criswell 1995, Jenkins et al. 1998, Fest et al. 2003).

The additional volume thus gained will enable the first moon workers to live and work in better and more comfortable conditions. In the following missions, it is probable that more structures, prefabricated and easily mountable, will be brought from Earth, for increased crew size and for added "necessities". But the next big step as far as construction works is concerned will be the realization of the first lunar building formed mainly using local soil, lunar regolith.

This first lunar manufactured building will probably have walls and roof constructed using reinforced regolith, soil bags or gabions (Farrier 2000, Toklu 2000), to serve as radiation shielding at the same time. The entrance unit with air locks will probably be imported from Earth, and air tightening of the structure will be provided by tensile resistant textile of type used for space suits covering the inside of the structure. There will be post-tensioned adjustable and controllable intelligent tendons outside the building to account for the tensile forces created by the inside pressure.

Realization and use of this first building using mainly local materials will be a landmark for the lunar construction industry. This building will be followed by others where processing of lunar regolith will start and there will be room for other activities for a sustainable existence on the Moon. One output of the processed regolith will be lunar concrete. The production of the first lunar concrete will be another important landmark in lunar construction industry. The next landmark will be the realization of the first reinforcing material, and this will already correspond to a quite developed phase of lunar industry.

These considerations are briefly sketched on the flow chart given in Fig.2. It must not be forgotten that the course followed in drawing this chart is far from being unique. Actually, there will be other branches like using lava tubes or artificial caves obtained by use of explosives after fitting them for habitation (Daga et al. 1990).

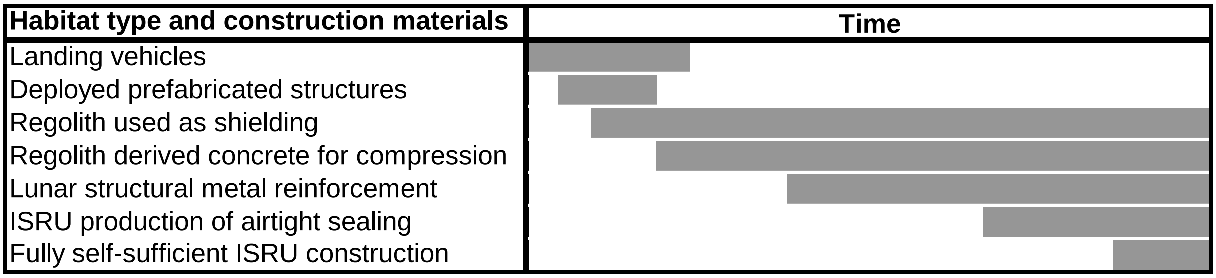

Figure 2. Bar chart for lunar construction industry

As far as construction is concerned, the main difficulties for establishment of a lunar basis can be considered as originating from three sources (Toklu & Järvstråt, 2003), namely the unaccustomed environment, the harsh and dangerous conditions, and the difficult access. The environment prevailing on the Moon present important differences as compared to those we are accustomed to on the Earth. This necessitates introduction of new concepts and standards of design and construction.

GLASSED DOMES? SORRY, NOT A GOOD IDEA!

The most commonly depicted "moon colony" construction is undoubtedly the glass dome – a giant dome of glass containing the entire colony in one dome, or a few domes. This is not only in science fiction, but unfortunately also in scientific and engineering articles on moon bases. The popularity is due to the fact that it is an aesthetically pleasing solution, which also provides a convenient view of the interior. Regrettably, the disadvantages of this design far outweigh the advantages. The well known fact that glass has poor tensile properties, especially when somewhat scratched or damaged, is not in itself a sufficient argument against this design, since pre-tensioned tendons could be used to put the glass in compression. However, glass is by its very transparency providing poor protection against radiation. Glass would let out infrared heat radiation during the night – putting shutters on an entire dome could of course be done, but an awkward chore. Worse, in order to protect against the dangerous components of sunlight during the day – the shutters would have to be very heavy and stay on during the day, completely destroying the glassed beauty of the dome. So, sorry, there will be no glassed domes on the moon - at least not for permanent habitation. They could have uses for short-term visits such as tourist scenery spots or for housing sporting events – where the aesthetics may drive economics and stays are short enough for radiation levels to stay acceptable. Even then, measures for improving radiation protection would surely be needed, such as special glass compositions with higher opacity for dangerous radiation, heavy shielding giving shadow for spectators, or simply not using the domes in daytime or during solar flares.

BURIED "TIN CANS"

The moon is covered with several meters of fine dust, regolith. Thus, just piling enough of this regolith over the "glass dome" is a straightforward means to provide a quick and highly accessible radiation protection. This has probably been the most commonly suggested type of habitat in more construction-oriented papers concerning moon bases. Of course, the dome then has no need for transparency and other materials than glass will be more appropriate. For a quick first shelter, the landing craft or other Earth imported rigid or inflatable "pressure vessels" will be much healthier and safer as habitat after radiation and meteorite shielding has been added by piling regolith dust on top. For long-term use, concrete, aluminium, cast basalt and other in-situ produced materials have been suggested. An important design consideration for production of these kinds of habitats is to avoid structural loads during construction that are radically different than the structural loads in use. For example, it may be necessary to gradually pressurise the habitat while very carefully and evenly covering with regolith. One disadvantage, beside the need to move and secure large volumes of regolith, would be the need for long entrance structures in order to reach surface without risk of regolith refill.

SEALED LAVA TUBES AND A MINE SHAFT SOCIETY

Having disqualified the pretty science fiction glass dome and seen that a hole in the dirt would do the trick, what would be more natural than going back to the cavemen for inspiration. But are there caves on the moon? Surely no limestone caves such as the more common caves on Earth, since these are formed in limestone deposited by ancient coral reefs. However, although not much geological activity remain, the Moon once had only a thin solid skin over a molten core and prehistoric volcanism is known to have been considerable. There are strong indications for the existence of large lava tunnels on the lunar surface. These natural cavities could be cleared, furnished and sealed to provide readymade shelters with a proven track record of resisting meteorite bombardment. The advantage of this solution is of course that the structure is pre-existing, while a significant disadvantage is that getting access, clearing them from rubble might be more effort than drilling a fresh tunnel where you want one. A significant advantage of lunar rock dwellings is that the load situation with regards to structural integrity is very similar to underground constructions on Earth – because the main load is the pressure of surrounding rock. As a matter of fact, even the airtight sealing problem has been successfully addressed in terrestrial underwater tunnels (although the acceptable leakage is much lower in a moon colony). Another idea for subterranean (or sublunarian, rather) dwellings would be to spend just a little more effort in the mining operation to leave a sealed and furnishable void when extracting the richest mineral veins for satisfying the material needs of the colony.

Regardless of how the sublunarian cavities have been formed, structural integrity as well as meteorite and radiation protection is provided by the surrounding rock. Habitat design and construction is then left with the smaller task of designing cavity shape and size to avoid any risk of cave-ins, sealing the cavities to keep the air in, and furnish for comfortable human habitation. Living in caves might not seem an attractive option, but there is no need at all for the "caves" to look like caves (Järvstråt, 2001). Think large shopping arcade – under roof but feeling a lot like outdoors. On the moon, the need for food production would make all open areas much greener than your ordinary shopping mall, with "sunlight lighting" needed for optimum plant growth. Still, care must be taken to enhance the feeling of nature or at least cultivated farmland. It will be an architectural and logistic challenge to arrange agricultural areas to provide recreation opportunities in as natural a setting as possible. The estimated need for 80 m^2 agriculture and common areas per person may not seem sufficient for your "forest walk". But, in a colony with 1000 persons and 20% of the space taken by rock support pillars it corresponds to 100 000 m^2. This could be arranged as four 5-meter wide strips of greenery stretching 5 kilometres. Each a quite nice walk or running track if you plan it right and probably more "nature" than used by most people today. And if you get tired of the layout or design of "your" track before the growth season is over, you can visit a neighbouring colony section.

ACTIVE STRUCTURES DESIGNED WITH ACTIVE DESIGN CONCEPT

For terrestrial constructions, the designers are accustomed to conceiving civil engineering products which have a certain capacity, beyond which the product can not be used due to failure or passage to a non-functional stage. Examples can be buildings that collapse when a level of earthquake magnitude is exceeded, or dams capable of resisting a predetermined level of water, or highways that become blocked whenever the traffic exceeds the design value. In the first example there is failure, in the second example there is passage to a non-functional stage perhaps coupled with failure, in the third example there is non-functionality. Although these are all undesirable, through millenniums since Hammurabi, a Babylonian king, who has put down the first written rules about collapsing houses, walls, dams and ditches around 1800 BC, the designers and constructors followed this procedure. Only very recently, with the advent of technology and accumulation of knowledge, the designers and constructors gained the capacity and consciousness necessary for distinguishing between the old way, passive design and passive structure, and the new way, active design and active structure.

When building for extraterrestrial conditions, perhaps the main difference compared to terrestrial conditions is that structures are much more safety critical. A structural collapse that would be damaging on Earth could well be fatal on the Moon, and any crack may be considered as failure because atmosphere will leak, possibly causing fatal secondary effects in short or long term. That means that for these structures new safety definitions and new ultimate load limits have to be defined. Further, the structure must be monitored in such a way that any part that comes close to the limiting values must be detected early enough. Lastly, should dangerous values be reached, the structure must behave in such a way that failure is prevented or reduced as much as possible. I.e., the structure must be “intelligent” enough to sense the danger and must act to prevent the damage, thus the term “intelligent ” or “smart ” or “active” structures. Such a scheme can be made possible by satisfying the following achievements:

- Active design: The structure must be designed as an active structure, with well-defined danger levels to trigger corrective actions (Utku 2002).
- Monitoring System: There must be sensors placed in the structure to measure critical stresses, loads, strains, and/or displacements.
- Control Units: There must be a redundant set of control units that automatically analyze and evaluate the measurements, decide on levels and types of actions to be taken, and command the actuators to respond accordingly.
- Active Structure: There must be actuators embedded in the structure commanded by the control units. These actuators will make the structure behave in such a way that temporary or permanent measures will be taken to prevent unacceptable damages.

An example can be the reduction of inside pressure of a structure to lower but still acceptable levels should stresses in tendons around approach prescribed limits.

Active structures thus will be able to respond automatically to any alterations suffered, especially if they could have dangerous consequences. Such measures will result in more economical constructions decreasing the safety factors that should be applied otherwise.

PASSIVE SAFETY AND STRUCTURAL HOMEOSTASIS

Although the use of active structures and automated control and regulation systems as described above will be necessary for emergency amelioration, it will also be necessary to design with highly stable self controlling processes whenever possible. Homeostasis is the process of environment auto-regulation encountered in many natural settings, such as societal insects. For example, it could be possible to employ self-convection driven by natural day-night temperature cycles to circulate the habitat air.

Air leakage could be reduced with a passive solution, such as providing a "buffer gas layer" between the habitat and the external vacuum, pressurised to higher levels than the habitat and containing gasses cheaper-than-air but reasonably safe.

Whenever the internal pressure is the dominant loading for a structure, it will be more economical to choose the most convenient structural type like sphere, cylinder, torus, spheroid or a similar form. For flexibility, hexagonal modules could be employed with advantage. It seems to be more appropriate to reinforce the walls of these structures by pre or post tensioned tendons. The tension in these tendons can be so arranged that the walls themselves can be under tension or compression. The latter choice seems to be preferable on the Moon since it is much easier to find or produce compression resistant materials than tensile resistant materials.

CONSTRUCTION EQUIPMENT AND METHODS

As seen above, moving, removing and handling regolith will be a major concern in creating a lunar base. Terrestrial construction equipment designs will need considerable modification to suit the conditions on the moon. The excavating force that is necessary under 1/6g conditions have been estimated and measured. It has been seen that although estimates give a ratio of ~1/6 for the soil breaking force necessary at 1/6g as compared to the force at 1g, experiments performed on NASA’s reduced gravity aircraft flights give this ratio as ~1/3 (Boles & Connoly, 1996). This shows that mass of the excavators will be only half as effective on the Moon than on the Earth. On the other hand, it is obvious that it will not be practical to transport to the Moon excavators as massive as those used on Earth.

The problem then is to have excavators with masses incomparably low than those accustomed on the Earth but more effective than expected. This may be possible by application of new concepts such as vibratory excavators or by pulling down the machines through cables or other means to increase the breaking force. A disadvantage of this procedure will be some loss in the freedom of operation of the machines but hopefully this will be compensated by the increase in effectiveness. In Fig. 3 such a consideration is visualized.

Another issue is that the vacuum on the moon would cause any lubricant oil to evaporate. Thus, unconventional solutions to lubrication must be found, such as solid lubricants or magnetic bearings (Gertsch & Gertsch 1990).

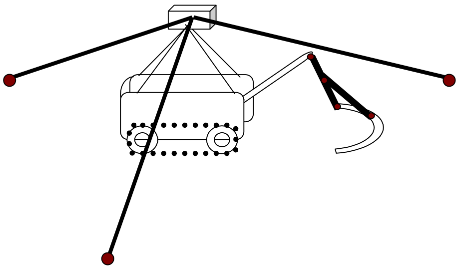

Figure 3. Excavator pulled down to increase effectiveness.

CONCLUSIONS

The material needs of modern community are covered by a rather limited set of manufacturing activities. Thus, self-sufficiency in small scale would be possible by optimising the overall production capacity of a community, even in such an extreme environment as a colony on the lunar surface. Construction loads on the moon are quite different compared to earth, with internal pressure being the dominant load while radiation protection and airtightness are the most important design considerations. Consequently, underground solutions will be the most attractive including caves or mines. It is important to design the colony interior giving an impression of outside in the agricultural sections so that these can also be used in recreation.

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