REVIEW

Engineering of lunar bases

Haym Benaroya\textsuperscript{a,}\textsuperscript{*}, Leonhard Bernold\textsuperscript{b}

\textsuperscript{a}Department of Mechanical and Aerospace Engineering, Rutgers University, New Brunswick, NJ, USA
\textsuperscript{b}Department of Civil Engineering, North Carolina State University, Raleigh, NC, USA

Received 14 May 2007
Available online 29 June 2007

Abstract

How do we begin to expand our civilization to the Moon? What are the technical issues that infra-structural engineers, in particular, must address? This paper has the goal of providing an overview of this fascinating area of structural engineering. Published work of the past several decades about lunar bases is summarized. Although many hundreds of papers have been written on these subjects, and only a few tens of these have been referred to here, it is believed that a representative view has been created. The paper is organized as follows. An overview is provided of possible structural concepts, including some details on the new lunar environment that engineers must design against. This is followed by a preliminary design study of a simple surface lunar structure for manned habitation. Concluding the paper is an introduction to construction issues that face the designed.

© 2007 Elsevier Ltd. All rights reserved.

Contents

1. Introduction ......................................................................................................... 278
2. The environment .................................................................................................... 279
  2.1. Loading, environment, and regolith mechanics ..................................................... 280
  2.2. Water on the Moon ............................................................................................. 282
3. Possible structural concepts ........................................................................................... 282
  3.1. Inflatable ..................................................................................................... 283
  3.2. Erectable ..................................................................................................... 283
  3.3. Concrete and lunar materials ..................................................................................... 284
  3.4. Lava tubes ..................................................................................................... 284
  3.5. Rovers as bases ................................................................................................ 285
  3.6. Geosynthetics .................................................................................................. 285
4. A recent design ..................................................................................................... 285
  4.1. Habitat layout .................................................................................................. 289
5. Construction in a new environment .................................................................................... 289
  5.1. Building a transportation infrastructure ................................................................ 289
  5.2. Driving wheels on sand ..................................................................................... 290
  5.3. Designing a lunar road ....................................................................................... 291
  5.4. The perils of lunar dust ....................................................................................... 292
  5.5. Steering clear of roads and dust ........................................................................... 294

\textsuperscript{*}Corresponding author.

E-mail address: benaroya@rci.rutgers.edu (H. Benaroya).

0094-5765/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2007.05.001
1. Introduction

Concepts for lunar base structures have been proposed since long before the dawn of the space age. We will abstract suggestions generated during the past quarter century, as these are likely to form the pool from which eventual lunar base designs will evolve. Also, one concept will be suggested which has particularly attractive qualifications for the surface lunar base. Significant studies have been made since the days of the Apollo program, when it appeared likely that the Moon would become a second home to humans. For an early example of the gearing up of R&D efforts, see the Army Corps of Engineers study [1]. During the decade between the late eighties to mid-nineties, these studies had intensified, both within NASA and outside the Government in industry and academe. The following references are representative: [2–15]. Numerous other references discuss science on the Moon, the economics of lunar development, and human physiology in space and on planetary bodies. An equally large literature exists about related policy issues. These topics are outside the scope of this paper, but should be viewed as equally important to the implementation of permanent manned settlements on the Moon and beyond. Human physiological and psychological issues are still unresolved.

Unfortunately, by the mid-nineties, the political climate turned against a return to the Moon to stay, and began to look at Mars as the “appropriate” destination, essentially skipping the Moon. The debate between “Moon First” and “Mars Direct” continues, although it is clear that the latter will do no more to the expansion of civilization into the Solar System than did the Apollo program. It is also clear that we do not have the technology and experience to send people to Mars for an extended stay. Physiological and reliability issues are yet unresolved for a trip to Mars. The Moon is our best first goal. In 2004, President George Bush defined his vision for the return to the Moon first, with Mars to follow.

The emphasis below is on structures for human habitation, a technically challenging fraction of the total number of structures likely to comprise the lunar settlement. The test for any proposed lunar base structure is how it meets certain basic as well as special requirements. On the lunar surface, numerous constraints must be satisfied by all designs, constraints very different from those for terrestrial structures. A number of structural types have been proposed for lunar base structures. These include concrete structures, metal frame structures, pneumatic construction, and hybrid structures. In addition, options exist for subsurface architectures and the use of natural features such as lava tubes. Each of these approaches can in principle satisfy the various and numerous constraints, but differently. Construction issues are also discussed subsequently.

A post-Apollo evaluation of the need for a lunar base has been made [16] with the following reasons given for such a base:

- lunar science and astronomy,
- as a stimulus to space technology and as a test bed for the technologies required to place humans on Mars and beyond,
- the utilization of lunar resources,
- establishment of a US presence,
- stimulate interest in young Americans in science and engineering, and
- as the beginning of a long-range program to ensure the survival of the species.

More recently, numerous studies have been made that support space tourism as an economically viable activity in space and on the Moon. These studies state that such tourism will be accessible to more than the very wealthy [17–19].

The potential for an astronomical observatory on the Moon is very great and it could be serviced periodically in a reasonable fashion from a lunar base. Several bold proposals for astronomy from the Moon have been made [20], and the debate on this continues to this day [21]. Nearly all of these proposals involve use of advanced materials and structural concepts to erect large long-life astronomy facilities on the Moon. These facilities will challenge structural designers, constructors, and logistics planners in the 21st Century [22,23]. One example is a 16-meter diameter reflector with its supporting structure and foundation currently being investigated by NASA and several consortia.

Selection of the proper site for a lunar astronomical facility, for example, involves many difficult decisions. Scientific advantages of a polar location for a lunar base [24] are that half the sky is continuously visible for...
astronomy from each pole and that cryogenic instruments can readily be operated there due to the fact that there are shaded regions in perpetual darkness. Disadvantages also arise from the fact that the sun will essentially trace the horizon, leaving the outside workspace in extreme contrast, and will pose practical problems regarding solar power and communications with Earth; relays will be required (Fig. 1).

2. The environment

The problem of designing a structure for construction on the lunar surface is a difficult one, discussed here in a necessarily cursory way. Many issues are not discussed, but will need to be tackled eventually. Some important topics not discussed here, but necessary in a detailed study, include:

- the relationships between severe lunar temperature cycles and structural and material fatigue, a problem for exposed structures,
- structural sensitivity to temperature differentials between different sections of the same component,
- very low-temperature effects and the possibility of brittle fractures,
- out-gassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials,
- factors of safety, originally developed to account for uncertainties in the Earth design and construction process, undoubtedly need adjustment for the lunar environment, either up or down depending on one’s perspective and tolerance for risk,
- reliability (and risk) must be major components for lunar structures as they are for significant Earth structures [25],
- dead loads/live loads under lunar gravity,
- buckling, stiffening, bracing requirements for lunar structures, which will be internally pressurized, and
- consideration of new failure modes such as those due to high-velocity micrometeorite impacts.

In a light flexible structural system in low-gravity, light structural members (e.g., composites cylinders that have wall-thicknesses on the order of $10^{-5}$ m) are sometimes designed to limit their load carrying capacity by buckling when that limit is met. In turn, the load would have to be re-distributed to other less loaded structural members. Such an approach offers possibilities for inflatable and other lunar surface structures where it would be simpler and less costly to include limit-state and sacrificial structural elements. Some of these discussions are well underway [26,27], in particular regarding the design process for an extraterrestrial structure.

Our purpose with this paper is to discuss the technical issues and provide some historical context. Important issues such as financing the return to the Moon, human physiological understanding, and many others are beyond the scope here. The focus for us is to provide the reader with a brief glimpse of the structural and structural-related engineering issues for human habitation on the Moon, and the difficulties associated with construction.

Important components in a design process are the creation of a detailed design and prototyping. For a structure in the lunar environment, such building and realistic testing cannot be performed on the Earth or even in orbit. It is not currently possible, for example, to experimentally assess the effect of suspended (due to one-sixth g) lunar regolith fines on lunar machinery. Apollo experience may be extrapolated, but only to a knowledge boundary beyond which new information is necessary.

Another crucial aspect of a lunar structural design involves an evaluation of the total life cycle, that is, taking a system from conception through retirement and disposition, or the recycling of the system and its components. Many factors affecting system life cannot be predicted due to the nature of the lunar environment and the inability to realistically assess the system before it is built and utilized.

Finally, it appears that concurrent engineering will be a byword for lunar structural analysis, design, and erection. Concurrent engineering simultaneously considers system design, manufacturing, and construction, moving major items in the cycle to as early a stage as possible in order to anticipate potential problems. Here, another dimension is added to this definition. Given the extreme nature of the environment contemplated for the structure, concurrency must imply flexibility of design and construction. Parallelism in the design space must
be maintained so that at each juncture alternate solutions exist that will permit the continuation of the construction, even in the face of completely unanticipated difficulties. This factor needs to be further addressed, and its implications clearly explored. A discussion of lunar design codes has already started [26,27].

NASA is now in the beginning stages of planning and design for a manned return to the Moon with the purpose of creating settlements for permanent habitation. This planning currently focuses on rockets and logistics, but is beginning to consider the broad range of considerations needed for the manned return to the Moon.

2.1. Loading, environment, and regolith mechanics

Any lunar structure will be designed for and built with the following prime considerations:

Safety and reliability: Human safety and the minimization of risk to “acceptable” levels are always at the top of the list of considerations for any engineering project. The Moon offers new challenges to the engineering designer. Minimization of risk implies in particular structural redundancy, and when all else fails, easy escape for the inhabitants. The key word is “acceptable.” It is a subjective consideration, deeply rooted in economics. What is an acceptable level of safety and reliability for a lunar site, one that must be considered highly hazardous? Such questions go beyond engineering considerations and must include policy considerations: Can we afford to fail?

One-sixth-g gravity: A structure will have, in gross terms, six times the weight bearing capacity on the Moon as on the Earth. Or, to support a certain loading condition, one-sixth the load bearing strength is required on the Moon as on the Earth. In order to maximize the utility of concepts developed for lunar structural design, mass-based rather than weight-based criteria should be the approach of lunar structural engineers. All of NASA’s calculations have been done in kg-force rather than Newtons. Calculations are always without the gravity component; use kgf/cm² as pressure, for example.

In the area of foundation design, most classical analytical approaches are based on the limit-state condition. That means that the design is based on the limit of loading on a wall or footing at the point when a total collapse occurs, that is, the plastic limit. Since many of the structures on the Moon require accurate pointing capabilities for astronomy and communications, for example, a settlement-based design method would be more useful. Chua et al. [28] propose a nonlinear hyperbolic stress strain model that can be used for the lunar regolith in a finite element analysis. They also show how the finite element method can be used to predict settlement of the railway under a support-point of a large telescope. Chua et al. [29] further show how a large-deformation capable finite element program can be used to predict the load-displacement characteristics of a circular spud-can footing, which was designed to support a large lunar optical telescope.

A note against assuming that less gravity means a footing can support more load: if soil can be assumed to be linearly elastic, then the elastic modulus is not affected by gravity. However, the load bearing capacity of a real soil depends on the confining stress around it. If the soil surrounding the point of interest is heavier because of a larger gravity, the confining stress would be higher and the soil at the point of interest can support a higher load without collapsing.

Lunar soil (regolith) mechanics has been exhaustively explored in the 1970s. Much of the work was approached from an interpretation based on classical soil mechanics. Newer work and development of non-linear stress–strain models to describe the mechanics of the lunar regolith can be found in Johnson et al. [30], and Johnson and Chua [31]. Chua et al. [32] show how structure–regolith simulations can be done using the finite element approach.

Internal air pressurization: The lunar structure will be a life-supporting closed environment. It will be a pressurized enclosed volume with an internal pressure of 6.9 × 10⁴ to 10.3 × 10⁴ Pa. The enclosure structure must contain this pressure, and must be designed to be “fail-safe” against catastrophic and other decompression caused by accidental and natural impacts. Internal pressurization offers challenges to all lunar structures, but especially the inflatable concept.

 Shielding: A prime design consideration is that the structure be able to shield against the types of hazards found on the lunar surface: continuous solar/cosmic radiation, meteorite impacts, and extreme variations in temperature and radiation. In the likely situation that a layer of regolith (lunar soil) is placed atop the structure for shielding, the added weight would only partially (in the range of 10–20%) balance the forces on the structure due to internal pressurization mentioned above. In addition to general shielding, special radiation shelters will be needed during periods of increased solar activity.

Shielding against micrometeorite impacts is done by providing dense and heavy materials, in this case compacted regolith, to absorb the kinetic energy. Lunar rocks would be more effective than regolith because of their fracture toughness, but rocks are more
difficult to obtain and much more difficult to place atop surface structures. Some suggest that for shielding purposes alone, it is better to design and place human-rated structures underground. This may be so, but it is then necessary to factor in the added costs and difficulties of subsurface work.

Much effort has been devoted to determining the damage effects on human beings and electronics resulting from nuclear weapon detonation and little is being done to determine long-term sustained low-level radiation effects, such as those that would be encountered on the Moon. According to Silberberg et al. [33], during the times of low solar activity, the annual dose-equivalent on humans on the exposed lunar surface may be about 0.3 Sv and the dose-equivalent over an 11-year solar cycle is about 10 Sv, with most of the particles arriving in one or two gigantic flares lasting one to two days. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 0.05 Sv, which is the allowable level for radiation workers (0.005 Sv for the general public). A shallower cover may be inadequate to protect against the primary radiation and a thicker cover may cause the secondary radiation, which consists of electrons and other radiation as a result of the primary radiation hitting atoms along its path.

In recent years, there is a move away from silicon- and germanium-based electronic components towards the use of gallium arsenide. Lower current and voltage demand, and miniaturization of electronic components and machines would make devices more radiation hardened.

Radiation transport codes can be used to simulate cosmic radiation effects since it is not possible to do that in the laboratory. One such code that has been found to be effective is LAHET [34] developed at the Los Alamos National Laboratory.

Vacuum: A hard vacuum surrounds the Moon. This will preclude the use of certain materials that may not be chemically or molecularly stable under such conditions. This is an issue for research.

Construction in a vacuum has several problems. One would be the possibility of out-gassing of oil, vapors, and lubricants from pneumatic systems. Hydraulic systems are not used in space for this reason. The out-gassing is detrimental to astronomical mirrors, solar panels, and any other moving machine parts because they tend to cause dust particles to form pods. For more discussion on construction challenges in the extraterrestrial environment, see Chua and Johnson [35]. Another problem is that surface-to-surface contact becomes much more abrasive in the absence of an air layer. The increase in dynamic friction would cause fusion at the interfaces, for example, a drill bit fusing with the lunar rock. This is of course aggravated by the fact that the vacuum is a bad conductor of heat. The increase in abrasiveness at interfaces also increases wear-and-tear on all moving parts, for example, railways and wheels.

Blasting in a vacuum is another interesting problem to consider. When the explosive in a blast hole is fired, it is transformed into a gas, the pressure of which may sometimes exceed 100,000 terrestrial atmospheres. How this would affect the area around the blast on the Moon and the impact of ejecta resulting from the blast is difficult to predict. Keeping in mind that a particle set in motion from the firing of a rocket from a lander could theoretically travel half way around the Moon, the effects of surface blasting on the Moon would be something to be concerned about. Discussion of the tests involving explosives which were performed on the Moon can be found in Watson [36]. Joachim [37] discussed different candidate explosives for extraterrestrial use. The Air Force Institute of Technology [38] studied cratering at various gravities and/or in vacuum. Bernold [39] presented experimental evidence from a study of blasting to loosen regolith for excavation.

Dust: The lunar surface has a layer of fine particles that are disturbed and placed into suspension easily. These particles cling to all surfaces and pose serious challenges for the utility of construction equipment, air locks, and all exposed surfaces [40].

Lunar dust consists of pulverized regolith and appears to be charged. The charge may be from the fractured crystalline structure of the material or it may be of a surficial nature, for example, charged particles from the solar wind attaching themselves to the dust particles. It was reported [41] that the dust particles levitated at the lunar terminator (line between lunar day and lunar night) may be due to a change in polarity of the surficial materials. Johnson et al. [42] discuss the issue of lunar dust and its effects on operations on the Moon. Halajian [43] and Seiheimer and Johnson [44] studied the adhesive characteristics of regolith dust.

Ease of construction: The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures be designed for ease of construction so that the extra-vehicular activity of the astronaut construction team is minimized. Construction components must be practical and, in a sense, modular, in order to minimize local fabrication for initial structural outposts. More detail is provided in a subsequent section on construction.

Chua et al. [45] discuss guidelines and the developmental process for lunar-based structures. They
presented the governing criteria and also general misconceptions in designing space structures. For example, a device that is simple, conventional looking, and has no moving parts is preferred over one that involves multiple degrees of freedom in an exotic configuration involving a yet to be developed artificial intelligence control, if the former meets the functional requirements. Another misconception is that constructing on the Moon is simply a scaling of the effects of similar operations on Earth and that theoretical predictive tools, especially those performed with computers, can accurately predict events. It is also a misconception that astronauts would have to work around the structure rather than designing the structure in such a way as to make construction easy for the astronauts.

**Use of local materials:** This is to be viewed as extremely important in the long-term view of extraterrestrial habitation. But feasibility will have to wait until a minimal presence has been established on the Moon. Initial lunar structures will be transported for the most part in components from the Earth.

The use of local resources, normally referred to as ISRU (in situ resource utilization) is a topic that has been studied, now more intensely because of the possibility of actually establishing human presence on the Moon, Near-earth-orbit (NEO) and Mars. Some of the earlier work is found in Johnson and Chua [46].

### 2.2. Water on the Moon

In a recent development, it appears that there may be water-ice in some craters near the poles of the Moon. It was suggested that water/water-laden comets and asteroids may have deposited the water. If water does exist in those craters, it was conjectured by Chua and Johnson [47] that the moisture distribution may consist of water-ice mixing with the regolith to saturation or near saturation, and reducing outwards according to the matric suction pressure (which is influenced by the particle size distribution). Since the gravitation potential is relatively small compared to the matric suction potential, the water would have been drawn laterally or even upwards over some distance. (Note: since the regolith has no clays, unlike Earth, there would not be an osmotic suction component to influence moisture migration.) The extent of this unsaturated zone is primarily influenced by how fast the water vapor condensed at the bottom of the crater, which has temperatures as low as $-230\,^\circ\text{C}$. The Lunar Prospector Mission team indicated that the moisture content in the regolith at the bottom of the crater might be between 0.3% and 1%.

### 3. Possible structural concepts

Various concepts have been proposed for lunar structures. In order to assess the overall efficiency of individual concepts, decision science and operations research tools have been proposed, used [2] and demonstrated [3]. Along these lines, various concepts are compared [48] using a points system for an extraterrestrial building system, including pneumatic, framed/rigid foam, prefabricated, and hybrid (inflatable/rigid) concepts (Fig. 2).

In a pioneering lunar structural design study, Johnson [49] presented the then available information with the goal of furthering the development of criteria for the design of permanent lunar structures. In this work, the lunar environment is detailed, lunar soil from the perspective of foundation design is discussed, and excavation concepts reviewed. An excellent review of the evolution of concepts for lunar bases up through the mid-1980s is available [50] as is a review of more recent work on lunar bases [12]. Surface and subsurface concepts for lunar bases are surveyed [51] with a recommendation that preliminary designs be considered which focus on specific applications. America’s future on the Moon is outlined as supporting scientific research, exploiting lunar resources for use in building a space infrastructure, and attaining self-sufficiency in the lunar environment as a first step in planetary settlement. The complexities and costs of building such a base will depend on the missions for which such a base is to be built.

A complete Earth–Moon infrastructure [52] uses proven technologies and the National Space Transportation System (NSTS) for early development of a lunar outpost. Transfer vehicles and surface systems are developed so that the payload bay of the Shuttle can be utilized in transport. The lunar outpost structural

---

Fig. 2. Early, Apollo era Boeing concepts for lunar settlement.
scheme separates radiation protection from module support allowing easy access, installation, and removal of elements attached to the Shuttle trusses. Of course, the shuttle is being phased out as the space station is being completed, and new rockets will be used to settle the Moon.

Several types of structures have been proposed for lunar outposts. A preliminary design of a permanently manned lunar surface research base has been briefly studied [53] with criteria for the base design to include scientific objectives as well as the transportation requirements to establish and support its continued operations. Grandl [54] suggests in his design study a modular lunar base built of at least six cylindrical modules. These are assembled on the lunar surface using a special crane. The cylinders are double-shell with regolith in between.

3.1. Inflatables

A pillow-shaped structure is proposed [55] as a possible concept for a permanent lunar base. The proposed base consists of quilted inflatable pressurized tensile structures using fiber composites. Shielding is provided by an overburden of regolith, with accommodation for sunlight ingress. These studies of the inflatable concept are continued [56] with consideration of the foundation problem and additional reliability concerns and analysis [57]. This concept is a significant departure from numerous other inflatable concepts in that it shows an alternative to spheroidal-inflatables and optimizes volume for habitation. Inflatable structural concepts for a lunar base are proposed [58] as a means to simplify the erection process while lessening the costs. The inflatable structure is suggested as a generic test bed structure for a variety of application needs for the Moon [59]. Design criteria are also put forward [60].

Another pressurized membrane structure is proposed [61,62] for a permanent lunar base. It is constructed of a double-skin membrane filled with structural foam. A pressurized torus-shaped substructure provides edge support. Shielding is provided by an overburden of regolith. The construction procedure requires shaping the ground and spreading the uninflated structure upon it, after which the torus-shaped substructure is pressurized. Structural foam is then injected into the inflatable component, and the internal compartment is pressurized. The bottoms of both inflated structures are filled with compacted soil to provide stability and a flat interior floor surface. Backfilling is a difficult operation to carry out through an airlock. It will, of course, be crucial to ensure that the interior is dust-free.

Finite element simulations of inflatable structures are needed because it is very difficult to reproduce a hard vacuum and low gravity condition on Earth. The finite element modeling would have to be large-deformation capable, have membrane elements (which are essentially beam elements that are without bending stiffness and has axial tensile stiffness but not the axial compression stiffness). The program should also ideally be able to model regolith–structure interaction. GEOT2D [32] is a program that has the capabilities needed to simulate inflatable structure–regolith interaction (Figs. 3, 4).

3.2. Erectables

An expandable platform is suggested [63] for a structure on the Moon. The structural concept consists of various geometrically configured three-dimensional trussed octet or space frame elements that are utilized both as building blocks and as a platform for expansion of the structure. Examples of the shapes to be used include tetrahedral, hexahedral, octahedral.

A concept has been proposed [64] for using the liquid oxygen tank portions of the space shuttle external tank assembly for a basic lunar habitat. The modifications of the tank, to take place in low Earth orbit, will include the installation of living quarters, instrumentation, air locks, life support systems, and environmental control systems. The habitat is then transported to the Moon for a soft landing. This idea, if proven economically feasible, may provide the most politically palatable path to the lunar surface, with the added advantage that many of the necessary technologies already exist and only need resurrection.

A semi-quantitative approach to lunar base structures is provided [65]. Some attention is given to economic considerations and the structural concepts included could be developed in the future.

A modular approach to lunar base design and construction is suggested as a flexible approach to developing a variety of structures for the lunar surface.

Fig. 4. An inflatable habitat similar to this could represent part of an outpost, forerunner to a permanent inhabited lunar base. Twenty years after the original manned Moon landing, a group of scientists and engineers at the Johnson Space Center (JSC) are considering the return to the Moon. The return would not be merely to explore but to learn to live and work on another planetary surface. Since 1986, a number of concepts for going to the Moon, living on its surface and adapting to its unique environment have been developed at JSC by designers who drew on experience reaching many years into the past. The habitation system depicted here may be different than represented. Actual scenarios and elements will be based on long-term strategies of the civilian space program, technological advances and public and Congressional input. The artist has depicted here, along with the inflatable habitat a construction shack and related solar shield, connecting tunnel regolith bags for radiation protection, thermal radiation experimental six-legged walker, solar power system for the lunar oxygen pilot plant and other elements. This concept was developed during the Lunar Base Systems Study undertaken by the Advanced Programs Office in the Engineering Office at JSC during the period 1986–1988. The study was performed by the Advanced Programs personnel with contractor support from Eagle Engineering, Inc. and Lockheed Engineering and Sciences Co. (NASA graphic number S89-26097 March 1989).

[66]. In a related vein, a membrane structure is suggested for an open structure that may be utilized for assembly on the lunar surface [67]. A tensile-integrity structure has been suggested as a possible concept for larger surface structures [68].

3.3. Concrete and lunar materials

A structural analysis and preliminary design of a precast, prestressed concrete lunar base is reported [69]. In order to maintain structural integrity, and thus air tightness, when differential settling is possible, a floating foundation is proposed. All materials for such a lunar concrete structure, except possibly hydrogen for the making of water, may be derivable from lunar resources.

The possibility of utilizing unprocessed or minimally processed lunar materials for base structures, as well as for shielding, may be possible [70] by adopting and extending terrestrial techniques developed in antiquity for harsh environments. A variety of materials and techniques are discussed which are candidates for unpresurized applications.

The use of indigenous materials is considered [71,72] for the design of a tied-arch structure. The study is extensive and detailed. Also included in this study is an exposition on lunar materials.

Construction using layered embankments using regolith and filmy materials (geotextiles) is viewed as an option using robotic construction [73], as are fabric-confined soil structures [74].

In order to avoid the difficulties of mixing concrete on the lunar surface due to lack of water, it has been suggested that a sulfur concrete be examined [75]. Sulfur is readily available on the Moon.

3.4. Lava tubes

Ideas regarding the utility of constructing the first outposts under the lunar surface have been proposed. A preliminary assessment is provided [76] of a lunar outpost situated in a lava tube. It is concluded that an architectural solution is needed to the problems surrounding the development of a lunar outpost, and that lunar surface structures are not the best approach. Rather, it is suggested that subselene
development offers real evolutionary potential for settlement.

In another structural approach, fused regolith structures are suggested [77,78]. In this case, the structures are small and many, and reside on the surface. A prime advantage offered for planning numerous smaller structures is safety and reliability. The premise of this work is to use the Sun’s energy to fuse regolith into components. Such ideas are being considered for the creation of a road system (79).

3.5. Rovers as bases

Some have suggested using pressurized rovers as permanent or semi-permanent bases. This has the advantage that the settlers can move sites as conditions or needs warrant. A disadvantage is that the size of the settlement is very limited and activities such as farming and manufacturing become almost impossible (Fig. 5).

3.6. Geosynthetics

Some recent papers suggested using geosynthetics as soil reinforcement to construct earth structures such as berms, walls, and slopes. There are several problems that have to be considered in order for this to be a reality.

- Plastic materials are susceptible to degradation when subjected to radiation.

- The glass transition temperature of many if not all of the geosynthetics used on Earth is well above the cold temperatures that are encountered on candidate sites including that on the Moon. This would make the plastics brittle thus rendering it useless as reinforcing elements.

- There is little experience on how geosynthetics fare in a hard vacuum and respond to the relatively more abrasive regolith.

4. A recent design

The structure in Fig. 6 is based on Ruess et al. [80]. Key environmental factors affecting lunar structural design and construction are: one-sixth \( g \), the need for internal air pressurization of habitation-rated structures, the requirement for shielding against radiation and micrometeorites, the hard vacuum and its effects on some exotic materials, a significant dust mitigation problem for machines and airlocks, severe temperatures and temperature gradients, and numerous loading conditions—anticipated and accidental. The structure on the Moon must be maintainable, functional, compatible, easily constructed, and made of as much local materials as possible.

Cast regolith has been suggested as a building material for the Moon. The use of cast regolith (basalt) is very similar to terrestrial cast basalt. The terms have been used interchangeably in the literature to refer to the same material. It has been suggested that cast regolith can be readily manufactured on the Moon by melting regolith and cooling it slowly so that the material crystallizes instead of turning into glass. Virtually no material preparation is needed. The casting operation is simple requiring only a furnace, ladle and molds. Vacuum melting and casting should enhance the quality of the end product. More importantly, there is terrestrial
experience producing the material; but it has not been used for construction purposes yet.

Cast basalt has extremely high compressive and moderate tensile strength. It can easily be cast into structural elements for ready use in prefabricated construction. Feasible shapes include most of the basic structural elements like beams, columns, slabs, shells, arch segments, blocks and cylinders. Note that the ultimate compressive and tensile strengths are each about ten times greater than those of concrete.

Cast basalt also has the disadvantage that it is a brittle material. Tensile loads that are a significant fraction of the ultimate tensile strength need to be avoided. The fracture and fatigue properties need further research (Table 1).

It should be feasible to use cast regolith in many structural applications without any tensile reinforcement because of its moderately high tensile strength. However, a minimum amount of tension reinforcement may be required to provide a safe structure. The reinforcement could be made with local materials.

Cast regolith is most suited for use in structures that are dominated by compression. However, using prestressed applications will offer a wide variety of shapes and structures. Prestressing tendons can be made from lunar materials.

Since it is extremely hard, cast regolith has high abrasion resistance. This is an advantage for use in the dusty lunar environment. It may be the ideal material for paving lunar rocket launch sites and constructing debris shields surrounding landing pads. The hardness of cast basalt combined with its brittle nature makes it a difficult material to cut, drill or machine. Such operations should be avoided on the Moon. Production of cast regolith is energy intensive because of its high melting point. The estimated energy consumption is 360 kWh/MT.

The structure will be human-rated, meaning that it will be shielded and can be pressurized upon a human presence. The presence of a structural shell on the Moon, awaiting human arrival, has enormous implications on the logistical planning of man’s return to the Moon. All the volume that would normally be allocated for bringing structural materials to the Moon can now be replaced with other items. This leads to an enormous saving in time and money.

Determining the dimensions of a lunar base habitat is a very complex task. Numerous factors like crew size, mission duration and function of the base as an industrial or scientific outpost influence the necessary habitat size. Hence, a global approach considering the necessary habitable volume per person will be pursued. Habitable volume is interpreted as free volume, excluding volume occupied by equipment or stowage.

As demonstrated by the Gemini missions, relatively short duration missions of up to two weeks can be endured by a person restrained to a chair most of the time. The habitable volume per crewmember in Gemini was 0.57 m³. Currently, the NASA Man Systems Integration Standards (NASA STD3000) [81] recommend a minimum habitable volume at which performance can be maintained for mission durations of four months or longer of about 20 m³. Despite this recommendation, a design volume (living and working areas) of 120 m³ per person for a lunar habitat has been recommended, based on research of long-term habitation and confined spaces. This value is about equivalent to the volume per crew member onboard the International Space Station.

The next question is to find an optimum floor height. Proposed floor heights for lunar habitats range from 2.44 to 4.0 m. People moving in low gravity will certainly require more vertical space than on Earth. They will lift off the floor higher while walking and especially when trying to run. Therefore, a floor height of 4.0 m seems most suitable and will therefore be used henceforth.

However, floor height is not equal to clear height. Support systems like lighting and ventilation will use 0.5 m up to 1.0 m of this space. This leaves in most cases about 3.5 m for the actual habitable volume. With these numbers fixed, one ends up with 34.4 m² floor area per person. The total floor area depends not only on crew size but also on the amount of equipment and stowage space that is needed. A summary for different crew sizes is given in Table 2.

### Table 1
Typical properties for cast regolith

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>N/mm²</td>
<td>34.5</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>N/mm²</td>
<td>538</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>kN/mm²</td>
<td>100</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>3</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>10⁻⁶/K</td>
<td>7.5–8.5</td>
</tr>
</tbody>
</table>

### Table 2
Total needed floor area with respect to crew size

<table>
<thead>
<tr>
<th>Crew size</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitable area (m²)</td>
<td>206</td>
<td>275</td>
<td>343</td>
<td>412</td>
</tr>
<tr>
<td>+20% for equipment and stowage (m²)</td>
<td>41</td>
<td>55</td>
<td>69</td>
<td>82</td>
</tr>
<tr>
<td>Total area (rounded up) (m²)</td>
<td>250</td>
<td>320</td>
<td>415</td>
<td>500</td>
</tr>
</tbody>
</table>
Now, having determined the total floor area, one can begin to size the structure. Depending on the chosen structural system, one has to find the most efficient span of the main structure and, depending on the structural system chosen, the spacing between primary structural elements. The necessary clear floor height can govern the span for some concepts, e.g., arches. The layout of the habitat is also very important at this point.

Regolith, upon which the lunar structure is built, needs to be understood from a foundation engineering view. The bulk density of regolith ranges from 0.9 to 1.1 g/cm³ near the surface and reaches a maximum of 1.9 g/cm³ below 20 cm. The average is at 1.7 g/cm³.

- The porosity of the regolith surface is about 45.
- Cohesion of undisturbed regolith is $c = 0.1 - 1.0$ kN/m².
- The friction angle is about $30° - 50°$.
- The regolith’s modulus of subgrade reaction is typically 1000 kN/m²/m.
- The compressibility ranges from $C_c = 0.3$ (loose regolith) to 0.05 (dense regolith).
- Interparticle adhesion in the regolith is high. It clumps together like damp beach sand.

This work idealizes the lunar soil using the modulus of subgrade reaction. All structural analysis calculations are thus done with the soil simulated by springs of stiffness $C_c = 1000$ kN/m²/m. It is a simplified method and a more detailed study of the regolith mechanics might be needed in the future.

First, the shape and rise of the arch were determined. A single floor layout is preferred to avoid additional structural mass for internal flooring and reduce the size of the main structural members at the same time. Therefore, a rise of 5 m was chosen for the arch. Fig. 7 shows how the space within the arch will be divided into the different functional areas.

On Earth, where gravitational loads usually govern our design, parabolic arch shapes are most efficient. An arch can be designed to be only in compression with little or no bending moment introduced into the structure. Bending moment should be avoided wherever possible as it is a very inefficient way to transfer the loads to the foundations. Simple tension or compression is much more efficient and is henceforth one of the design goals.

On the Moon, however, the governing load is not gravitational, but rather internal pressurization. The circular arch is the more suitable structure because no bending moments are introduced in the arch. An in-plane two-dimensional analysis is found to be sufficient; no major three-dimensional effects are expected since the structure runs continuously in the third direction only. Internal forces, member stresses and deflections are calculated using finite element software.

The bending moment in the tie is a result of soil structure interaction (Fig. 8). It depends on the ratio...
of foundation to soil stiffness. The final bending moment in the tie can only be determined iteratively because every change in tie stiffness results in a change in bending moment that in turn may require a different tie cross-section. Thus, the final bending moment distribution will only be available after the structural design is finished.

The mass of a body never changes, but its weight depends on the gravitational acceleration. On the Moon the designer has to be careful when applying gravitational loads. They are usually given as weight-based in kilo-Newton or kilo-Newton meters. For lunar analysis, they have to be calculated using the lunar gravitational acceleration. The resulting loads will be only about \( \frac{1}{6} \) of similar ones on Earth. For the static analysis of the structure, the main load cases identified in addition to the structure’s self-weight are:

1. Internal pressure \( p = 69 \text{ kPa} \).
2. Regolith covering the whole structure \( q = 8.3 \text{ kPa} \).

The loads for the regolith cover assume the regolith can be placed uniformly on the structure. If instead loose soil is simply heaped upon the top of the structure, the resulting load will be trapezoidal, not uniform (Fig. 9).

Most of the loads described above may act at the same time. There are also a number of different scenarios that the designer needs to account for: starting with construction stages, the structure being initially pressurized with the regolith not yet on top of it, next the regular operational mode with all loads acting, and finally a planned or accidental decompression. The maximum effect on the structure has to be found using load combinations. For each scenario only the loads that increase the stresses in the structure are to be included. Self-weight is always present. Four combinations were used to find the maximum stresses in the members:

1. Internal pressure plus floor loads.
2. Regolith cover plus installation loads.
3. All loads.
4. Half the regolith cover (during construction).

Two main conclusions result from the preliminary structural analysis. First, the arch segments can have a uniform cross-section. It is possible but not necessary to adjust the arch cross-section to the distribution of internal forces since these are almost uniform. Second, in order to get an efficient cross-section for the tie it has to be adjusted to the distribution of internal forces. The bending moment has the shape of a parabola, so it was decided to give the tie a similar shape. Fig. 10 shows the principal shape of the tie/floor/foundation.

The regolith foundation will need to be sintered before the structure is fabricated and will result in a higher modulus of subgrade reaction and therefore lower deflections of the tie. It does not affect the arch deflections. Calculations show that the modulus of subgrade reaction would have to be increased about tenfold to get in the range of desired deflections. This is very likely not possible to be achieved by sintering the regolith. Some
additional reinforcing is needed. More research data is needed for this topic.

4.1. Habitat layout

The question of lunar base layouts is a very complex one and deeply rooted in architectural and operations considerations. However, providing different modules for research, habitation, manufacturing, storage, etc., seems like a reasonable approach. These modules can be arranged in a multitude of scenarios. The five basic configurations are: Linear, Courtyard, Radial, Branching, and Cluster. These possibilities can affect design and construction.

5. Construction in a new environment

Site plans [82] and surface system architectures [83] are forcefully presented as being fundamental to any development of structural concepts.

One of the challenges to the extraterrestrial structures community is that of construction. Lunar construction techniques have differences from those on Earth, e.g., the construction team will operate in pressure suits, motion is dominated by one-sixth g, solar and cosmic radiation not shielded by an Earth-type atmosphere, and the existence of suspended dust at the construction site. An assessment is provided [84] of various construction techniques for the classes of structures and their respective materials.

Structural and architectural designs, along with manufacturing plants, and construction methods are discussed [85] for a habitable structure on the Moon using concrete modules. The module can be disassembled into frame and panels.

A qualitative study [86] is made of the design and construction of a lunar outpost assembly facility. Such a facility would be used to construct structures too large for transport to the Moon in one piece. The assembly facility would also be used to support operations and maintenance during the functional life of the lunar outpost. A series of trade studies are suggested on the construction of such an assembly facility.

Construction of a lunar base will at least partially rest on the capabilities of the Army Corps of Engineers. Preparations that are now underway are outlined [87] and challenges discussed [88].

All of the above are contingent on the “practical” aspects of building structures on the Moon. These aspects include the sort of machinery needed to move equipment and astronauts about the surface, the methods needed to construct in one-sixth g with an extremely fine regolith dust working its way into every interface and opening, and the determination of the appropriate layout of structures considering human safety and operations needs. Using harsh Earth environments such as the Antarctic as test beds for extraterrestrial operations is advocated [89].

The performance of materials and equipment used in lunar construction needs to be examined in terms of the many constraints discussed so far. Structures that are unsuitable for Earth construction may be adequate for the reduced-gravity lunar environment [62]. Several research efforts have been directed to produce construction materials, such as cement, concrete, and sulfur-based materials, from the elements available on the Moon [90–95].

Matsumoto et al. [96] present JAXA’s long-term vision for lunar exploration. The Japanese view their role as a major provider of technology in a multinational effort for the return to the Moon for a permanent manned presence.

The appendix to this paper provides a long list of structures that require study, and also lists the necessary tools/equipment, methods of operation/control, and most importantly how to construct structures within the lunar environment. Because most of the construction methods that have been developed since the beginning of mankind are adapted to fit and take advantage of the terrestrial environment (i.e., soil characteristics, atmosphere with oxygen, 1 g gravity), technologies that are common on Earth will either not work on the Moon, are too costly, or too inefficient.

5.1. Building a transportation infrastructure

Roads and highways are critical to the efficient transportation of people and goods between two places on Earth because they provide a leveled road free of obstacles such as trees and stones. According to the Wikipedia: “A road is an identifiable route or path between two or more places. Roads are typically smoothed, paved, or otherwise prepared to allow easy travel.” As Fig. 11 indicates NASA’s vision of a lunar base does include roads, bridges, streetlights and footpaths based on terrestrial designs.

While the readers’ eyes might focus on the two astronauts in the forefront or the hovering lunar lander in the background, the eye of a construction engineer immediately focuses on the road surface, bridge and the apparent footpath leading up the ridge to the A-frame buildings in the background. Especially interesting is the fact that the road leading to the bridge shows furrows apparently created by the
wheels of vehicles, a road resembling one through the desert.

The construction of durable roads on Earth comprises several phases beginning with the removing of the natural soil, to be replaced with layers of foundation material put according to specific recipes. Each layer, clustered into a road-base and road surface, fulfills one of the following functions: (1) distribute the concentrated loads under the wheels/tracks, (2) provide sufficient traction for traveling up-hill pulling a load and braking, (3) resist abrasion by wind and rain, and (4) allow the rain water to drain easily to the side of the road. While designers of a lunar road do not need to worry about rain and wind, they will have to consider other factors such as one-sixth g and the dust. Introduced in the next section are some of the basic concerns of using the lunar surface as the main means of transporting material and people over “natural roads.”

5.2. Driving wheels on sand

Besides smoothing the ride, the main function of a car tire is to spread the total load of the vehicle while providing traction through its treads. A key tire design criterion is the pressure between the tire and the driving surface. That pressure is one of the main causes of road degradation. The objective of the road engineering effort is to design the road with a bearing capacity that is larger than the maximum expected vehicle load. Should that maximum be exceeded on a regular basis, as done by overloaded trucks on side-roads, the road-base will eventually disintegrate. While highway engineering has learned a lot about the expected behavior of different road designs under terrestrial conditions, a designer of lunar roads has no knowledge base and standards on which to rely.

There are some basic terrestrial principles that will apply, albeit in a modified manner, on the Moon. The four pictures presented in Fig. 12 show some of the most common “realities” of driving a vehicle across sandy surfaces. Lightweight vehicles with high chassis seem to do well while wheels can easily get stuck if the bearing capacity of soft sand is too small for the pressure under the tire. Regolith on the lunar surface contains a large percentage of small soil particles. Thus, Fig. 12(c) highlights the potential outcome of picking up speed in an environment that only has one-sixth g. The last picture illustrates the result of a road that is deteriorating because it cannot support the traffic. As shown, ripples have formed causing the vehicle to vibrate, adding dynamic forces that eventually will cause it to become non-trafficable.

Early empires that covered large areas realized that survival depended on quick military movements. The most famous road builders, albeit not the first, the Romans, created a vast transportation infrastructure connecting most of Europe. Without sophisticated equipment and materials they were capable of building long lasting thoroughfares.

Fig. 13(a) reveals that the space under the cobble stones is made up of several strata on top of compacted clay, each with a different mix of stones. As a matter of fact, one of the key accomplishments of Roman engineers was the insight that the thickness of layers could be adjusted to the local situation and the expected traffic. For example, when the underground was relatively solid, some could be built thinner, and vice versa. The gravel below the sand-gravel layer served as drainage that let the rainwater seep into the ditches on the side of the road. If done properly, a road built in this manner would not develop potholes because the yearly freezing and thawing cycles would not be able to weaken the foundation.

The diagram in Fig. 13(c) highlights the most crucial function of the layers, namely the distribution of the point load $F$, where the wheel touches the road surface, through the various layers down to the natural soil. The changing slopes of the force diffusion cone results in increasing areas $A_1$ through $A_3$ with the effect that the soil pressures, $\sigma_1$ through $\sigma_3$, are getting smaller. A road design that allows the wheel load to disperse in a way that the resulting pressures are smaller than the bearing capacity of each layer will support a high quality surface for a long time. As Fig. 13(b) depicts, the principle of layering is still being applied today and will also be relevant for lunar road construction. While there is no rainwater to consider on the Moon, the effect of the drastic temperature variations, vacuum, differences
in gravity and soil characteristics will offer unknown challenges.

5.3. Designing a lunar road

The analysis of the regolith samples brought back from different areas of the Moon show that the size distribution of soil particles, mostly consisting of powdery fines, will make it impossible to create a road-base with significant strength. What makes conditions even more difficult is the lack of gravel in large amounts, a material that is created through a natural abrasion process in rivers here on Earth. Thus, similar to the Romans, lunar road engineers need to replace the unsuited regolith with material mixes designed for the specific needs of a road. The high proportion of very small particles caused the Apollo astronauts major problems. While they do not stay “airborne” for a long time, the dust-blankets that are produced create havoc in mechanical joints, motors, locks, and air-filters.

The pulverized regolith is the result of an abrasive action created by small space debris that bombarded the material on the lunar surface for millions of years. As a result, pictures show us large and small boulders embedded in dessert-like material consisting of mineral fragments, impact glasses, and particles called agglutinates that are mineral and rock fragments stuck together by impact glass. Using common methods of densification, static or vibratory compactors, will only densify the top layer of the “powder.” In fact, it might even loosen the soil underneath. Bernold [97,98] reported that the strength of the mainly cohesionless regolith can only be increased by reducing the percentage of fines to 10%. In addition, a hardened surface should be generated in order to eliminate dust and the possible forming of ruts. Such road surfaces could be made of flat rocks or crushed stone. On the other hand, it might be possible to utilize the microwave sintering method that has been proposed by Taylor and Meek [79] if its durability and trafficability are acceptable.

In order to discuss how much of the in situ regolith could be used for road construction, an average lunar regolith is used [99]. As the base-line, a terrestrial standard for road construction recommended by the National Stone Association [100] is being used. Table 3 shows the result of a volume comparison using
Table 3
Example regolith balance-chart for a lunar road-base

<table>
<thead>
<tr>
<th>Sieve size (a)</th>
<th>Nominal size (mm) (a)</th>
<th>Lunar regolith (b) (%)</th>
<th>Average for road-base (a) (%)</th>
<th>Regolith volume balance (%)</th>
<th>Useable regolith in place (%)</th>
<th>Useable regolith collected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1″</td>
<td>25.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1/2″</td>
<td>12.5</td>
<td>0</td>
<td>19</td>
<td>+19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td># 8</td>
<td>2.36</td>
<td>0</td>
<td>44</td>
<td>+44</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td># 16</td>
<td>1.18</td>
<td>5</td>
<td>11</td>
<td>+6</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td># 30</td>
<td>0.60</td>
<td>3</td>
<td>7</td>
<td>+4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td># 50</td>
<td>0.30</td>
<td>10</td>
<td>7</td>
<td>−3</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td># 100</td>
<td>0.15</td>
<td>20</td>
<td>4</td>
<td>−16</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td># 200</td>
<td>0.07</td>
<td>50</td>
<td>8</td>
<td>−42</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>&lt;#200</td>
<td>&lt; 0.07</td>
<td>12</td>
<td>0</td>
<td>−12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>27</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

(a) National Stone Association [100].
(b) Mitchell et al. [99].

standard sieve sizes. Each sieve has a specific mesh with a nominal opening (size). Particles that do not pass are collected and measured by volume while smaller ones pass through to the next level.

As column 3 reveals that 5% of the largest size particles are regolith particles that pass a mesh opening of 2.36 mm but not 1.18 mm. The 0% in rows with sieve sizes larger than # 16 indicates that the samples collected by the astronauts did not contain any of those dimensions. On the other hand, 50% of the regolith passed an opening of 0.15 mm but collect in sieve # 200. Finally, 12% represents a silt-type powdery material and passes even the # 200 sieve.

However, as column 4 reveals, a good soil mix for a road-base does not contain any particles that pass a 0.07 mm opening. As a consequence, 42% that is collected in sieve # 200, and the 12% that pass it, have to be taken away. Column 5 lists the necessary volumes for each size that have to be added (+) and removed (−). As shown, in addition to the 54% fines, 3% of # 50 and 16% of # 100 have to be sieved out.

To build a road-base with the example mix design, one needs to dispose of 73% of the regolith. On the other hand, the plus signs in rows of larger size material indicate that those volumes need to be added. Fig. 14 depicts the material flow, in percent of desired total volume, needed to build a solid road foundation.

As Table 1 shows, 44% of # 8 and 19% of 1″ (12.5 mm) are not present in an average sample and have to be added. As Fig. 9(a) and (b) point out, stones of that size can be gained by either raking the top layer of the surrounding regolith or by crushing larger rocks or boulders down to the desired sizes. While the raking option may require that a large area be searched, a crushing operation is not only energy intensive, but also means that rocks and boulders have to be transported and will create dust during crushing, sieving and mixing. In addition, such a plant will require a significant amount of maintenance due to the abrasiveness of the material to be handled and dust that was found to be an extremely critical “fiend.” In fact, breaking down rocks into smaller sizes emulates the slow process responsible for the pulverized surface regolith encountered by the astronauts during the Apollo missions. Apollo 16 astronaut John Young clearly stressed the danger in overlooking the dust problem in his technical de-brief: “Dust is the number one concern in returning to the Moon” [101]. He surmised that: “The severity of the dust problems were consistently underestimated by ground tests, indicating a need to develop better simulation facilities and procedures.”

The next section is a brief reminder why dust has to be considered and avoided when designing a lunar road.

5.4. The perils of lunar dust

Fifty percent of the regolith is smaller than fine sand and approximately 20% is smaller than the “dusty” 0.02 mm that preserved the astronaut’s boot prints. According to Gaier [101] the dust-related hazards can be sorted into nine categories: (1) vision impairment, (2) incorrect instrument readings, (3) dust coating, (4) loss of traction, (5) clogging of mechanisms, (6) abrasion, (7) thermal control problems, (8) seal failures, and (9) inhalation. Based on observations during the Apollo
program the largest source of dust generation were the landings and take-offs.

Two other important dust generators are walking–jumping–kneeling and the moving wheels of the rover [101]: “Dust was elevated by walking, as evidenced by how quickly the EMS around their feet and ankles became dirty. . . . On several occasions astronauts lost their balance and tumbled to the surface, or intentionally went down on one knee to better observe the surface. In all cases, the result was dust adhering to the EMS, which could not be brushed off.”

Finally, the overall problem that the lunar dust creates was summed up by Gene Cernan, an Apollo 17 astronaut: “I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.” Dust adheres “. . . to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it’s restrictive friction-like action to everything it gets on. For instance, the simple, large tolerance, mechanical devices on the rover began to show the effects of dust as the EVAs (External Vehicular Activity) went on” [101] From those first-hand observations it is apparent that the creation of dust has to be avoided or at least mitigated while potential intrusion paths carefully blocked.

Each of the three pictures in Fig. 15 illustrates problems that have to be considered for the construction of a trafficable road. Fig. 15(a) is a reminder that the pulverized top is not only easily compacted by a boot but it easily kicked up and adheres itself to anything it comes in contact with. Regolith’s mineralogical characteristic causes it to be extremely abrasive, scratching gauge dial covers to make them unreadable or wearing out the suits of astronauts. “Dust found its way into even the smallest openings, and when the Apollo 12 crew stripped off their clothes on the way back to Earth, they found that they were covered with it. Dust was also transferred to the Command Module during Apollo 12 and was an eye and lung irritant during the entire trip back” [101].

Fig. 15(b) exemplifies the simple fact that the rover engineers did not consider the “adhesive” capability of the regolith when designing the fender. Despite more effective fenders that were built after the shown quick-fix, dust covered the rover: “By the middle or end of the third EVA (during Apollo 17), simple things like bag locks and the lock which held the pallet on the Rover began not only to malfunction but to not function at all. They effectively froze. We tried to dust them and bang the dust off and clean them, and there was just no way. The effect of dust on mirrors, cameras, and checklists is phenomenal” [101].
Fig. 15 underlines the potential dangers in driving a wheeled vehicle over surfaces with insufficient bearing capacity on Mars. David [102] reported that: “NASA’s Opportunity Mars rover has run into a sandy snag. All of its six wheels have sunk in deep into a large ripple of soil.” It took the JPL team 5 weeks to maneuver the rover out of the dune which they later named the “Purgatory Dune.” As shown, the dusty material clung itself to the solid wheel surface, thus eliminating the traction effect of the tracks. The only thing that saved it from being permanently “stuck” was its light weight.

5.5. Steering clear of roads and dust

The wheel-based mode of transportation is not the only mature technology to move people and cargo. One alternative, discussed in earlier publications [97,98,103], uses lightweight cables and luffing masts to transport pressurized cars, robotic equipment and cargo. In such a scenario, the construction of permanent roads can be avoided. Fig. 16 offers a view of a lunar base where roads and bridges have been replaced with a two-way cable-based infrastructure.

Cable-based systems are able to take advantage of the lower gravity force which allows even small diameter cables to span long distances with minimal deflection while carrying large loads.

Fig. 16 highlights another important feature of an adaptable cable system, the luffing mast. Using a pin or ball joint at the bottom and connecting luffing/guy wires at the top, a mast can be swiveled around the bottom joint. Controlled by electric winches at either end of the guiding wires, a suspended cable car can be placed at any location that is covered by the track cable, reaching from mast to mast. The lowering of the car can be accomplished by either winching or by relaxing the tension in the track cable causing the maximum suspension at the connection point of the car. Depending on the transportation needs of future bases, cars can be made to move personnel in pressurized cabins, operate robotic arms and grippers, or haul cargo. Also indicated in Fig. 16 is the potential of moving the landing area of the lunar landers away from the habitat area, thus eliminating a major source of dust and the negative impact of a crash.

6. Concluding summary

We have presented a summary of current thinking regarding some of the issues surrounding the engineering and construction of structures for long-term lunar habitation. Many ideas have been put forth over a span of almost half a century. Our goal here has been to introduce the reader to the key structural issues that need to be addressed by engineers as they design a surface structure for the lunar surface, for habitation.
Appendix A. Building systems

Types of applications

Habitats:

- people (living and working);
- agriculture;
- airlocks: ingress/egress;
- temporary storm shelters for emergencies and radiation;
- open volumes.

Storage facilities/shelters:

- cryogenic (fuels and science);
- hazardous materials;
- general supplies;
- surface equipment storage;
- servicing and maintenance;
- temporary protective structures.

Supporting infrastructure:

- foundations/roadbeds/launch pads;
- communication towers and antennas;
- waste management/life support;
- power generation, conditioning and distribution;
- mobile systems;
- industrial processing facilities;
- conduits/pipes.

Application requirements

Habitats:

- pressure containment;
- atmosphere composition/control;
- thermal control (active/passive);
- acoustic control;
- radiation protection;
- meteoroid protection;
- hazardous material containment;
- maintenance equipment/tools.

Supporting infrastructure:

- all of the above;
- regenerative life support (physical/chemical and biological);
- industrial waste management.

Types of structures

Habitats:

- landed self-contained structures;
- rigid modules (prefabricated/in situ);
- inflatable modules/membranes (prefabricated/in situ);
- tunneling/coring;
- exploited caverns.

Storage facilities/shelters:

- open tensile (tents/awning);
- “tinker toy”;
- modules (rigid/inflatable);
- trenches/underground;
- ceramic/masonry (arches/tubes);
- mobile;
- shells.

Supporting infrastructure:

- slabs (melts/compaction/additives);
- trusses/frames;
- all of the above.

Material considerations

Habitat:

- shelf life/life cycle;
- resistance to space environment (uv/thermal/radiation/abrasion/vacuum);
- resistance to fatigue (acoustic and machine vibration/pressurization/thermal);
- resistance to acute stresses (launch loads/pressurization/impact);
- resistance to penetration (meteoroids/mechanical impacts);
- biological/chemical inertness;
- reparability (process/materials).
Operational suitability/economy:

- availability (Lunar/planetary sources);
- ease of production and use (labor/equipment/power/automation and robotics);
- versatility (materials and related processes/equipment);
- radiation/thermal shielding characteristics;
- meteoroid/debris shielding characteristics;
- acoustic properties;
- launch weight/compactability (Earth sources);
- transmission of visible light;
- pressurization leak resistance (permeability/bonding);
- thermal and electrical properties (conductivity/specific heat).

Safety:

- process operations (chemical/heat);
- flammability/smoke/explosive potential;
- out-gassing;
- toxicity.

Structures technology drivers

Mission/application influences:

- mission objectives and size;
- specific site-related conditions (resources/terrain features);
- site preparation requirements (excavation/infrastructure);
- available equipment/tools (construction/maintenance);
- surface transportation/infrastructure;
- crew size/specialization;
- available power;
- priority given to use of lunar material and material processing;
- evolutionary growth/reconfiguration requirements;
- resupply versus reuse strategies.

General planning/design considerations:

- automation and robotics;
- EVA time for assembly;
- ease and safety of assembly (handling/connections);
- optimization of teleoperated/automated systems;
- influences of reduced gravity (anchorage/excavation/traction);
- quality control and validation;
- reliability/risk analysis;
- optimization of in situ materials utilization;
- maintenance procedures/requirements;
- cost/availability of materials;
- flexibility for reconfiguration/expansion;
- utility interfaces (lines/structures);
- emergency procedures/equipment;
- logistics (delivery of equipment/materials);
- evolutionary system upgrades/changeouts;
- Tribology.

Requirement definition/evaluation

Requirement/option studies:

- identify site implications (Lunar soil/geologic models);
- identify mission-driven requirements (function and purpose/staging of structures);
- identify conceptual options (site preparation/construction);
- identify evaluation criteria (costs/equipment/labor);
- identify architectural program (human environmental needs).

Evaluation studies:

- technology development requirements;
- cost/benefit models (early/long-term);
- system design optimization/analysis.

References


[81] L.A. Pieniazek, L. Toups, A lunar outpost surface systems architecture, SPACE 90 engineering, construction, and


