# PISCES Student Design Competition: A Novel Lunar Outpost

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## ABSTRACT

The Pacific International Space Center for Exploration Systems (PISCES) conducted its first student design competition in 2007. The winning entry from Honolulu Community College described a novel four-sphere habitat for a lunar outpost capable of supporting six crew members and six visitors. Arguments are advanced for the selection of a habitat of this type over those previously advanced by others for lunar outposts. This report briefly describes the proposed habitat.

## INTRODUCTION

The Pacific International Space Center for Exploration Systems (PISCES) (http://pisces.uhh.hawaii.edu/) has been established at the University of Hawaii, Hilo, with the goal of becoming a major center for education, technology development and testing of space exploration systems. Development of PISCES began in 2007 with funding from the State of Hawaii. Lunar robotic systems field tests will be conducted by NASA at a PISCES test site in November 2008 in field terrains that are analogous to lunar landscapes on the flanks of Hawaii's Mauna Kea volcanic edifice. A longer-term PISCES goal is to develop an analog lunar outpost in which astronauts, ground controllers, and students can conduct long-duration exercises that are relevant in preparing for lunar outpost operations, and where architectures and systems for lunar outposts can be tested. The affiliation with the University of Hawaii will make it possible for PISCES to conduct faculty and student lunar outpost research that promises to expand our understanding of what it means to live and work on another planet.

One of the first projects undertaken by PISCES in 2007 was the organization of the PISCES student design competition. The topics were chosen by the student teams, but all had to be relevant to the construction and operation of a lunar outpost. Three teams from nine entries were selected to travel to Hawaii to participate in the first annual PISCES Conference in November 2007. These three teams all chose topics relevant to the design and operation of lunar outposts. Honolulu Community College (HCC) fielded a team of architectural/ engineering technology students who focused on the design of a long-term habitat. Their work forms the basis for this paper.

## THE LUNAR OUTPOST DESIGN

The long-term goal of PISCES is to develop an analog lunar outpost. The Honolulu Community College (HCC) team approached the habitat design as a multifaceted engineering problem in an architectural context, focusing on the real problems of building structures for the Moon. A central premise of the study is that habitats in themselves represent a very important objective for the establishment of a lunar outpost, both to ensure the accomplishment of lunar outpost objectives and as a test case for humans living and working on another planetary body.

Fig. 1. A team member inspecting carbon fiber materials at the college's Marine Education and Training Center on Sand Island in Honolulu. Instructors are Certified Composites Technicians.

The full report of the HCC team is available at honolulu.hawaii.edu/aec/lunar_habitat.pdf. It focuses on such design elements as a self-contained sanitation system, composition of the proposed carbon fiber shell, biomass production, food storage, natural lighting, human muscle maintenance and nutrition, oxygen production, decontamination, wireless machine-to-machine communi-cations and sensor networks, and siting. It introduces a new and unique solar energy system involving ultra-efficient 3D nano-tower arrays (Honolulu Community College, 2007) -- in short, much more than can be covered in this brief paper.

The work of the team was aided by representatives from the science, aeronautics, aviation, and marine technology programs at HCC, as well the Geophysics and Planetology program at the University of Hawaii at Manoa. It involved invited guest presentations, a Naval submarine tour at Pearl Harbor where several potentially related systems are used, carbon fiber technology and science lab demonstrations, computer simulations, and literally hundreds of hours of individual research, drawing, and construction.

Although construction of an analog outpost on Earth will involve technologies and materials that might be different from what they would be on the Moon, an analog at a terrestrial setting on Earth will yield valuable information about the construction, systems, and operation requirements of an actual lunar outpost.

## DESIGN CRITERIA

Transportability. Any habitat must be capable of being transported to the lunar surface, removed from the landing vehicle, and positioned. Size, weight, configuration, and ease of handling are critical. The envisioned habitat payload will be neither light nor small. The system must fit into the available space transportation system (e.g. ARES with a 27-foot payload shroud) and be within the mass-lifting capabilities of the rocket. On the Moon, site preparation equipment and additional equipment and supplies will need to be transported ahead of time or at the same time. Developing a large-capacity transport vehicle that can land on the moon will be essential. Helping to make this possible will be the moon's one-sixth gravity and absence of variable weather conditions. The team's design is based on the transport vehicle being capable of landing on the lunar surface. An alternative would be a lander capable of individually delivering segments of the transport vehicle (each large enough to contain a habitat module) to the surface.

The team fully understands that current NASA plans for landers are not sufficient for landing the HCC habitat. The team also believes that greater delivery capabilities will be available by the time a longer-term, sustainable habitat is established. A short-term inflatable or unfoldable habitat capable of transport from Earth with currently envisioned transportation systems may be a legitimate first goal for lunar exploration. Our team, however, preferred to look ahead of current technologies to a time when it is possible to transport a more substantial habitat to the moon that is more self-sustainable than modules of the International Space Station and that has a potential for development and replication as a lunar outpost is developed. Placing a habitat on the Moon in which people can simply survive with a lifeline to Earth may not be sufficient, we believe, to sustain public interest and support. It must have a greater purpose as well as recognizable and not-too-distant benefits to life on Earth. Planning should be built on trust that essential and plausible new technologies will be developed. We know this is not always easy, and scientists are not particularly prone to risk-taking.

A large-capacity landing capability will have other uses as well and could become a key element in transporting large numbers of people and materials to and from the lunar surface.

Ease of Assembly or Construction. Although spacesuits will be thinner and more form-fitting, intricate or small scale tasks outside of the habitat will still be difficult. Any habitat should be as ready to use as possible upon placement. Assembly or construction tasks should be limited, simple, and easy to handle.

Mobility. Any separate or individual modules must be positioned upon unloading. Modules that can be moved into position and possibly repositioned or replaced later without heavy equipment should be best suited to the task.

Setup Efficiency. Time prior to actual occupancy will be limited, and time will be needed for many different tasks. Modules in which furnishings, piping, wiring, and equipment are pre-installed are preferable to modules requiring a lot of on-site installations. Just as on Earth, on-site installations are usually inferior to factory installations, they generally require more parts, there are greater chances of missing or wrong parts, they are seldom as compact, and the risk of injury or simply incorrect installation is greater. However, for a lunar habitat, there will always be tradeoffs between the ability of crews to assemble pieces on site and the cost of transporting large assemblies to the Moon.

Safety. Catastrophic or limited system failure should be manageable. The team believes that compartmentalized spaces are essential for safety. Occupants should be able to escape from a dangerous area to a safe one. An even safer design would be one where spaces are actually separated and energy, oxygen, water, medical supplies, and emergency communications systems are independent. Safety within the habitat will be much more important than on Earth where people can generally escape to the outdoors. On the moon, the outdoors is about the last place to go in an emergency.

Although the team proposes extensive wireless machine-to-machine (M2M) control and monitoring of the habitat shell, climate, biomass, aquaculture, and personnel by way of mesh networks, piping and much traditional wiring will still be needed. This was a major safety concern when considering other types of designs where probably most piping and wiring would be exposed and risk external wear, breakage, and personal injury. It is one of the reasons why the team decided on a hard shell habitat where piping, wiring, and much of the equipment needed to support the habitat will be accessible but hidden and out of the way. A more unobstructed interior will also make it easier to control dust that could be a significant problem in one-sixth gravity.

Depressurization for any reason will also be safer in a hard shell habitat. Rather than having to evacuate in the case of a major loss of air pressure and possibly a collapsing roof, personnel would be able to make repairs inside the habitat just as they would in space suits outdoors. The common presumption is that depressurization would be caused by meteorite impact or other failure in the enclosure, but it could just as well be caused by equipment failure requiring repair inside the module. A hard shell that is simply unaffected by pressure variations will also not fail due to simple stress and strain or affect on attached or nearby items.

Meteorites and moonquakes are also reasons for safety concern. Since meteorites do not disintegrate or slow in the absence of an atmosphere, the risk of impact is significant even if not great. In this respect, habitat size, strength, and shape are important. The frequency of severe moonquakes is low, but a habitat design that allows for ground movement should be preferred. The team designed a habitat that is supported by cushioned struts also used for leveling. Solar flares are another concern.

Strength. Any habitat must be strong enough to withstand stresses of loading, unloading, positioning, pressurization, extreme temperature variations, meteorite impact, moonquakes, and possible system catastrophe. The team has proposed a shell for its habitat that is continually monitored electronically for degradation even so slight that it is undetectable by human inspection. If a fault is ever detected, it is automatically repaired and documented (Mullaney, 2007).

Efficiency. With essentially no atmosphere, plant life, or bodies of water, energy on the Moon must be derived almost exclusively from solar radiation or possibly nuclear sources. For this reason, the habitat must be as energy efficient as possible. However, it must also provide for efficiency in the cycling of materials, such as atmospheric gas and water, which will require substantial energy.

An efficient design will emphasize the use of space and resources to support key objectives of the outpost. The initial habitat we propose includes only limited provisions for exploration equipment repair, storage of samples and remote monitoring devices, and equipment and supplies for extended explorations far from the habitat. These provisions will be important, but they will either have been provided by earlier ventures to the habitat site, or be provided later after the habitat has been established and expanded.

All space within the habitat should be used efficiently, the shape of the habitat should be the most appropriate for pressurization and the most efficient in terms of materials use, systems should be as self-maintaining as possible (especially with only six inhabitants), and modules should be similar in design for ease of replication upon expansion. All spaces or modules should be physically connected, and communications and service systems should be interconnected. At the same time, it should be possible to disconnect and maintain systems independently in any overall system-threatening emergency.

Expandability. Future expansion is inevitable. Survival and a degree of self-sufficiency will be the most important initial goals, but exploration, mining, and tourism activities will certainly follow. The design of additional modules should be easy to integrate with the initial habitat.

Livability. A habitat that offers freedom of movement, a variety of spaces ("changes of scenery"), relatively open areas, and private spaces in addition to common spaces is essential. A keynote speaker at the PISCES Conference, a participant in the Biosphere II experiment in Arizona, made this very clear (J. Poynter, personal communication). The technical problems in that habitat turned out to be minor in comparison to interpersonal problems that only grew worse over time in confinement. The problems had not been anticipated, and the problem-solving methodologies of scientists did not work. Other problems caused by confinement were mentioned to team members at the same conference by a person who spent four months in a Mars habitat experiment in Canada (Crites, 2008). It is quite reasonable to believe that such problems will be even more likely in a far more dangerous, unknown, and inaccessible environment such as that on the Moon.

One of the first places where these problems should be addressed in respect to a lunar habitat is in its physical design. Some of the relevant elements of this team's design are a central biomass that occupants should find inherently comfortable as well as an important part of the planned ecosystem, dome ceilings that seem more spacious than flat surfaces with corners and edges, high ceilings in a couple of the modules, a hard shell that feels safe rather than temporary, separate modules that are somewhat distinctive and serve different purposes, and private quarters in addition to common areas.

Contrary to what is evidenced by many other lunar habitat proposals, the team believes that any such habitat should probably be as large as it will be possible to land on the Moon. Planning, we believe, should involve social scientists as well as engineers, and emphasis should be placed on sustainability over sheer economics or a rush to simply get there.

## THE DESIGN

The general requirement to be met by the lunar outpost design is the long-term support of a crew of six persons, with provisions for six additional people during periods of crew change-out. The HCC team's solution is a four-sphere habitat. Each sphere is 26 feet in diameter, although the size can rather easily be reduced to 25 feet, or to 24 feet, which is the minimum before losing one of the three proposed floor levels. Each sphere has a distinctive function – one is devoted to individual sleeping quarters, another to biomass production, a third to communications, monitoring, and control operations, and a fourth to food storage, dining, and exercise.

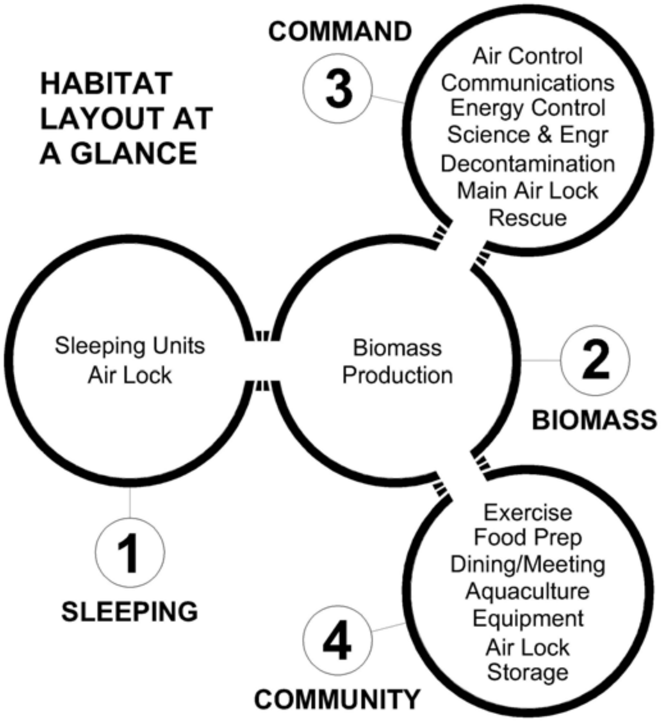



Fig. 2. The HCC 4-sphere design of a lunar habitat

There are several important reasons for proposing the sphere. The most important is that it is by nature and by far the strongest form known. Evidence exists in the strength of eggshells, large water and chemical storage tanks, and batted balls. External and internal forces are distributed three dimensionally and uniformly throughout. Like the well-known Bathysphere designed to withstand incredible pressure at extreme depths of the sea, a lunar habitat will need to withstand pressurization and extreme temperature variations. The sphere is also the most disaster resistant enclosure short of going underground. In Hiroshima, for example, a domed building was the only structure that survived the first atomic bombing in 1945.

Spheres use materials more economically than any other basic form (South, 1999). A sphere with the same interior space (volume) as a cube, for example, has nearly 20% less surface area. This means material, weight, and cost savings of nearly 20%. Energy requirements for heating and cooling are reduced by the same 20%. Spheres are energy efficient for other reasons as well. There are no distant corners, and natural air circulation is significantly aided by rounded surfaces. Although the rate of convection is *reduced* in one-sixth gravity, the need for savings and efficiency will be *greater* on the moon where energy conservation will be essential. The sphere is "nature's perfect form" – for these very important reasons.

Other reasons for choosing the sphere include ease of mobility and initial positioning on the lunar surface, unlimited surface orientation for power generation from sunlight, which might reduce or even eliminate the need for solar tracking devices and the potential for mechanical problems that come with them, rounded interior surfaces that counteract the sense of confinement (mentioned earlier), and greater interest that is essential to public support.

Rather natural first concerns about a 24- or 26-foot sphere are understandably about its size and weight. One-sixth gravity, though, very importantly mitigates both concerns. Although lightweight construction is envisioned for the spheres, their mass has not yet been determined. Everything else being equal, however, the weight of a 26-foot sphere on the Moon is equivalent to that of a 10'-7" sphere on Earth. On Earth, the sphere will be loaded into the transport vehicle by machine. On the Moon, it will be lifted up from the cargo hold much as the tiers of a jewelry box or fishing tackle box rise as the top is opened (better would be lowering the sphere from the bottom of an upright transport), guided down a ramp by rope and pulley, and rolled, wedged, and jacked into position by two people. Making it easier to roll will be the fact that because of its form, pushing against it at normal height will naturally be upward toward the center of mass.

Lightweight construction will also make the sphere very mobile on the lunar surface. The outer sphere of the shell (Fig. 3), it is estimated, will be a 1/2" thickness of multiple layers of Quadaxial® carbon fiber fabric (Owens Corning, n.d.) and epoxy with embedded protective sealing agents. It will be extremely strong and highly resistant to impact. An exterior coating of Awlgrip® will protect the shell during loading, unloading, and positioning on the moon. Applied to the interior surface of the outer sphere will be a 4" to 5" thickness of lightweight rigid insulation. And applied to that will be a 1/8" to 1/4" (depending on location) carbon fiber and epoxy interior liner. When the sphere is rolled, the outer 1/2" thickness will provide compression resistance while the carbon fiber liner will provide tension resistance. Just the opposite will be the case in respect to pressurization.

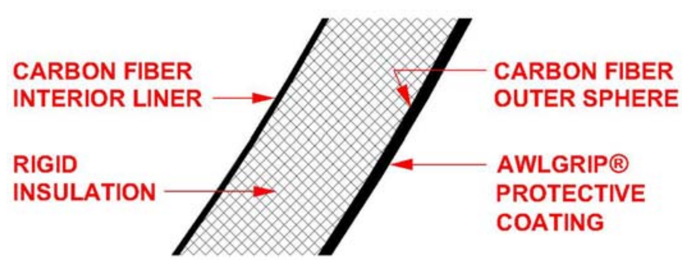



Fig. 3. Construction of the outer sphere shell

Interior partitions will be constructed of lightweight but strong 2" honeycomb panels similar to Hexcel's HexWeb® paneling (Hexcel Corporation, n.d.). Each sphere contains a ladder for easy and space-saving access to different floor levels. Ladders might pose a safety concern on Earth, but in one-sixth gravity, risk of injury will be negligible. Ladders will be constructed of 1/2" and 1" titanium tubing and weigh only about 40 pounds. Windows that weigh more than an equal area of sphere shell will be kept to a minimum for better thermal protection and weight savings. The only generously sized view windows will be located in the dining and exercise areas. These will serve the purpose of reducing the psychological effects of confinement (mentioned earlier) and provide views of Earth (very important according to NASA (Greg Byrne, personal communication) that are especially impressive because of Earth's size in the sky and its clarity. Natural light will be admitted principally through special light pipes that, unlike windows, will widely disperse light and make even small pipes very effective. The sphere shell will be fairly plain except for foot wells, handholds, and attached solar sheeting. On the interior, built-ins will reduce overall weight by eliminating the need for many fasteners and support devices, water and other piping will be lightweight plastic, and wireless systems will reduce much of the need for naturally heavy copper wiring.

Fig. 4. Ladder and hatch on USS PASADENA submarine that the team visited at Pearl Harbor, courtesy of the U.S. Navy

The spheres must be accurately positioned so that floors are level and passageways between the spheres are perfectly aligned. Prior practice on Earth should make near leveling and alignment fairly easy. Precise positioning will be achieved by adjusting exterior struts (four per sphere) that act as bracing, by jogging with one or more simple lever devices engaged with recessed handholds in the shell, or by rolling the sphere near its final position onto a gel-surfaced matting and simply slipping the sphere as needed. Precise positioning of a sphere that can be rolled, twisted, and rotated is naturally much easier than with any flat-floored or irregularly shaped form.

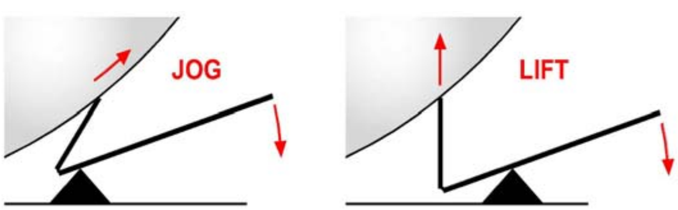



Fig. 5. A simple lever connected to a handhold can be used to jog or lift the sphere

THE HABITAT MODULES

All four of the sphere modules incorporate a space for wiring, piping, and equipment on the lower level where the curved shell wall meets the ceiling (Fig. 6). Access is primarily through covered openings in the main level floors. Three of the spheres have entry/exit air locks, and each of these is connected to a plenum in the mechanical space. Air is forced back and forth between the plenum and the air lock for pressurization and depressurization of the air lock.

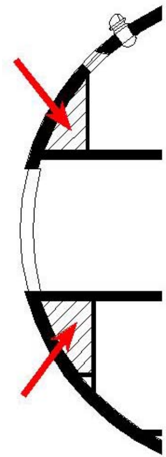
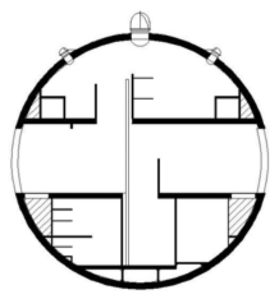


Fig. 6. Spaces are available for pipes and

Certain mechanical spaces also contain sewage settlement tanks, oxygen generators, fans, pumps, and other special purpose equipment. Another space, but more of a raceway, is on the upper level in three of the four spheres where the curved shell wall meets the floor.

Limited spaces below the bottom floor in all but the biomass sphere provide storage space for batteries to power the habitat during periods of no sunlight. Alternatively, the spaces might be designed to house a carbon fiber flywheels to store energy for use during prolonged periods of darkness, which will likely be the case at any site on the lunar surface.

Sphere 1 is devoted almost exclusively to individual living quarters – four units on the main level and two units and an airlock on the lower level to accommodate a total of six people in the habitat. Each unit contains a built-in desk, built-in bed, and personal storage compartments. The units are small, emphasizing private spaces over common areas.



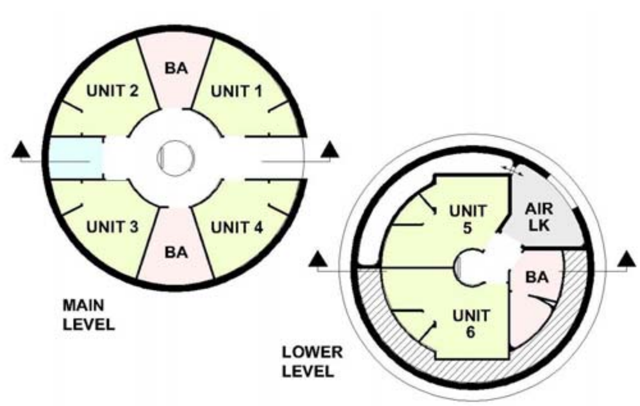



Fig. 7. Vertical section (above) and plans for Sphere 1. (Plans are simplified. More detail is in the full report).

It was found that not much space would be saved for other purposes by creating shared spaces unless bunk beds were planned and storage was reduced. Lightweight swinging doors were chosen because of their simplicity and familiarity. There is one bath for every two units. Bath facilities are components of a sanitation system that recycles all waste via settlement tanks and a treatment facility in the biomass sphere. The upper level of the sphere accommodates up to six additional occupants during personnel change-outs.

Sphere 2 is devoted primarily to biomass production. It has a single floor level with sludgy waste treatment facilities below and a suspended walkway above. The biomass area is far too small to support a complete ecosystem, but it is none-theless an important step toward self-sufficiency that will be more important the farther we venture from Earth. It is essentially a lab that also produces the only fresh fruit and vegetables available, and it helps support the environ-ment.

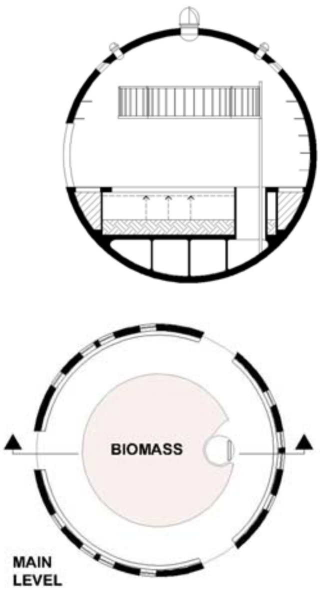



Fig. 8. The vertical section (above) and the floor plan for Sphere 2

Soil is created by mixing moon dust and gravel for bulk and texture with sludge from the treatment of human waste. Additional planting material is obtained from biodegradable containers, food leftovers, inedible parts of food products, and mis-cellaneous debris from plants. On the walls of the sphere are plastic or open mesh shelves for numerous but small hydroponic plants. Plants high in the sphere can be reached from the suspended walkway. The walkway itself has a lightweight mesh floor that filters light to the plants lower in the sphere.

The biomass sphere is the hub of the habitat. The main passageway in each of the other spheres provides a direct view into the middle of the biomass. The plants together with a high ceiling make it feel almost like outdoors in a familiar Earth environment. It is the primary relief from low ceilings and tight spaces.

Sphere 3 is devoted mostly to communications, moni-toring, and primary control operations. The main and upper levels are flexible in use. Tentatively, science and engineering labs are on the upper level and command-type facilities requiring more space are on the main level.

On the lower level are a combination main air lock and primary decontamination center, a secondary decon-tamination room, lunar exploration and maintenance facilities, and a rescue center close to the air lock. Entry to the habitat is mainly through this air lock, whereas the others are used primarily for emergency egress. The rescue center is designed for only emergency care, and equipment is similar to that in an ambulance of about the same size. Since personal quarters are not shared, medical recovery or isolation is available there if needed.

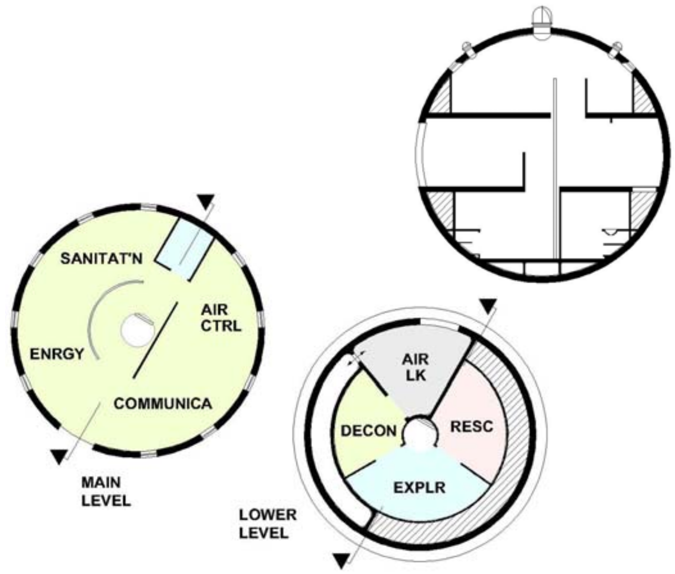
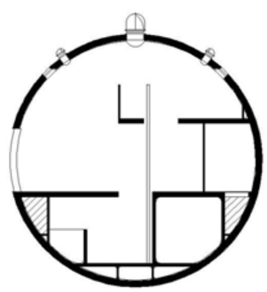



Fig. 9. Vertical section (above right) and floor plans for Sphere 3.

Sphere 4 is devoted primarily to personnel maintenance and well-being. Food is stored here, meals are taken, and exercising is done here. On the main level are a kitchenette, dining area that can also be used for group meetings and tabletop games, an exercise area, and a food storage room with composters. On the lower level are an air lock, water storage facility, an area for exposed machinery, and an aquaculture. In the ceiling above the aquaculture are glass-covered (actually plastic) apertures that admit light from higher in the sphere and permit walking over in the exercise area above. The upper level extends over only half of the sphere and is used for bulk food storage and other items. It also provides access to hanging plants over the dining and exercise areas.



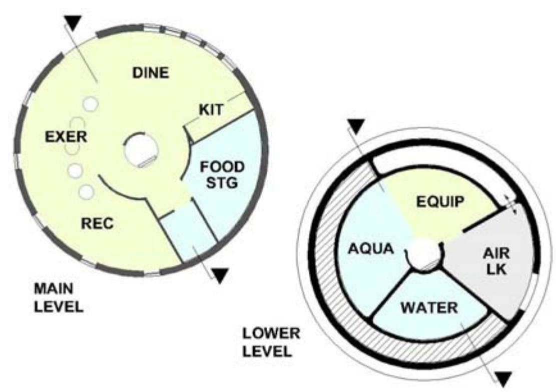



Fig. 10. Vertical section (above left) and floor plans for Sphere 4

OUTPOST LOCATION

Because of relatively moderate temperature variations and shortest periods of darkness at the poles, either lunar pole would likely be a suitable location for the habitat. The team, however, preferred the north pole because of a greater chance of water being found in ice or permafrost – and because of a greater chance of lava tubes being found there. The lava tubes might possibly be used for storage protected from dust or for personal protection from solar flares.

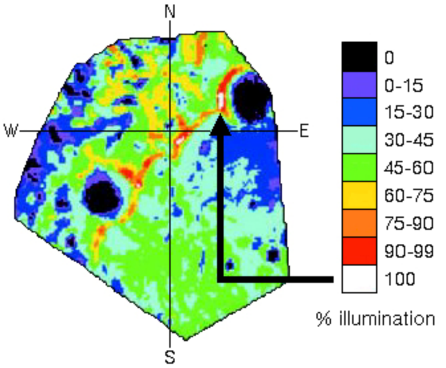



Fig. 11. Illumination conditions at the lunar north pole (reference)

As the moon is tipped at 1.5° to the ecliptic, it is most likely that no site will be permanently sunlit. Elevation might make a big difference, however, and some lunar experts believe that north polar peaks may be sunlit nearly 100% of the time. A team at Johns Hopkins University in 2004 identified an area on the rim of Peary crater as possibly a "perfect" site (Britt, 2005). The desirability of a habitat perched atop a crater rim, though, is uncertain. Lunar crater rims are very sharp and rugged. Even if a site could be found on a crater rim, getting to places away from the habitat might be nearly impossible. Further investigation should quite certainly be conducted before a specific site is recommended.

TECHNOLOGIES

As the habitat design was being developed, several technologies that may be of interest for lunar habitat design and that can be integrated well with spherical structures were identified. Two energy-related concepts are described here.

Tubular Skylights

A few small windows, in spite of no atmosphere or clouds to reduce sunlight, are not sufficient to adequately light the habitat, especially the biomass and of course during periods when one sphere after another is turned away from the sun. To both supplement window light and provide natural light during otherwise long periods of darkness in each sphere, tubular skylights are planned. These are similar to devices manufactured by SunPipe, Inc., Solalighting, Ltd., and other firms. They are installed in roofs (typically) and reflect light downward at a desired angle and frequently to lower floor levels and remote spaces.

A sun pipe is located at the very top of each sphere. Since sunlight enters from the side, light would pass through the dome rather than be caught in the pipe. To catch the light, we have installed a half dome-shaped reflector just inside the clear dome to catch and turn the light downward. The reflector can be rotated electronically or manually from inside the sphere. All of them are within reach, even from the suspended walkway over the biomass. Each reflector can be turned slightly each day or few days so that natural light is available continually regardless of side sunlight or shading. The sun pipe at the top of each sphere is 21" in diameter.

SunPipe's 21" model produces up to 3,000 watts of light (this or more should be available in the no-atmosphere environment of the moon) – 3,000 watts of light, 24 hours a day, every day, and without any electrical energy needed during periods of illumination

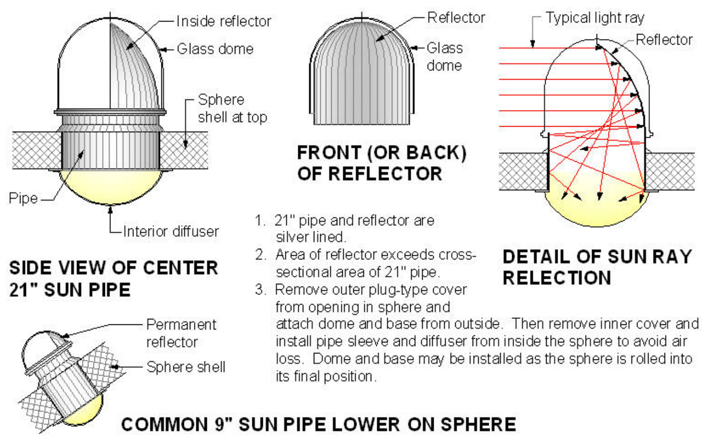



Fig. 12. Design of tubular skylights for spherical habitat.

Solar Power

Solar cell material will be pinned or otherwise attached to all sun-facing surfaces of all four spheres. In the absence of wind that could tear or disconnect them, they will be essentially trouble free. Two firms in California (Nanosys and Nanosolar) and another in Massachusetts (Konarka) are developing solar nanotechnology, and a number of products are currently on the market (Lovgren, 2005). Tiny solar cells are printed or sprayed onto a variety of materials, including flexible materials such as those appropriate for use on the habitat spheres. Because of the density of the cells and their ability to take advantage of the sun's infrared rays (which traditional silicon-based cells do not do), the technology is five to seven times more efficient than current technologies. The most important problems in development involve cost and distribution for mass production, neither of which should hamper application to the habitat.

In April of 2007, the Georgia Tech Research Institute, working with funding by the US Air Force, unveiled an even more efficient technology. Whereas most solar panels are flat, GTRI's design features an array of spaced-apart, micro nano-towers, like miniature highrise buildings separated by city streets. By being three-dimensional and spaced apart, the towers of cells both increase absorption area and trap photons that would otherwise be reflected and lost. The design also outperforms flat panel designs at times when sunlight is not directly overhead.

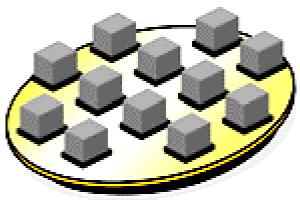


Fig. 13
Micro nano-tower solar array towers are 100 microns tall, 40 microns square, and separated by 10 microns

Fabrication of the cells begins with a silicon wafer, which can also serve as the solar cell's bottom junction. Researchers first coat the wafer with a thin layer of iron using a photolithography process that can create a wide variety of patterns. The patterned wafer is then placed in a furnace heated to 780°C. Hydro-carbon gases are then flowed into the furnace, where the carbon and hydrogen separate. In a process known as chemical vapor deposition, the carbon grows arrays of multi-walled carbon nanotubes atop the iron patterns.

Once the carbon nanotube towers have been grown, researchers use a process known as molecular beam epitaxy to coat them with cadmium telluride (CdTe) and cadmium sulfide (CdS) which serve as the p-type and n-type photovoltaic layers. Atop that, a thin coating of indium tin oxide, a clear conducting material, is added to serve as the cell's top electrode. The panels produce about 60 times more electricity than traditional panels (Toon, 2007). Voltage problems persist, however, but the potential of the technology is real.

The solar energy system described here may be supplemented by a solar power system placed earlier in the area of the habitat, depending upon general energy requirement calculations, sunlight conditions at the selected site, and methods chosen for generating and storing energy for possibly prolonged periods of darkness.

REMAINING ISSUES AND CHALLENGES

The habitat design presented here was developed by a team of students with limited resources and little experience in designing for space missions. There are other considerations that assuredly must be taken into account before a concept such as this can be adopted for a lunar outpost design. Some challenges for future study include:

- Design of a space transportation system to accommodate large habitats of this type.
- Weight reduction in the habitat elements that allows them to be carried by the smallest capacity lunar lander, which remains to be designed, and that is most likely larger and more capable than currently envisioned landers. The habitat described here, however, is designed to be delivered to the lunar site by the transport vehicle itself.
- Detailed consideration of subsystems – life support, lunar resource utilization, etc. to determine their probable requirements for equipment space, mass, and power in the habitat.
- Design of solar collection, distribution, and storage systems to provide electrical energy for the habitat, particularly during prolonged periods of darkness.
- Thorough consideration of all important activities of humans at a lunar outpost to determine the operational feasibility of the habitat design.
- Simulation of the habitat design in a terrestrial setting on Earth to further test the technological recommendations and operational effectiveness of the habitat design.

## CONCLUSION

The first annual PISCES student design competition has lead to an innovative student design for a lunar habitat. In the coming year, additional studies will be undertaken by PISCES, in consultation with NASA, of a concept for the PISCES lunar outpost analog. The results of the current study will be incorporated into that consideration. One clear problem that emerges is how to transition from the limited-capability landers and temporary facilities that are likely to be designed by NASA to a truly self-sustainable long-term habitat and industrial facility that must emerge if lunar exploration is to be a sustainable goal for humanity. The current study has begun to outline some possible pathways.

## ADDENDUM

Including Responses to Reviewer Comments

The team was composed of students in the Architectural, Engineering and CAD Technologies program at the University of Hawaii Honolulu Community College. All of the students were first-year students in April 2007 when the project was started, while second-year students were preparing for a portfolio review and graduation just a month later. In the fall of 2007, two incoming students joined the team.

Although a few students were interested in space missions and future technologies, none had a particularly strong background in space engineering or architecture, or a closely related science such as physics, geology, or astronomy. With the enthusiasm of a few, however, along with the involvement of faculty advisors who had at different times been involved in other space projects and events, plus film documentaries and guest presentations, interest and commitment to the project grew. Still, everyone was a full-time student, which required about six hours of daily class attendance (sometimes three hours per week per course credit hour), and about half of the students also had part-time jobs.

All of the work on the project was separate from class work due to the fact that the competition became known only after the start of the Spring 2007 semester when other plans and projects were in progress. Team members at the PISCES conference were quick to point out that one of the competing teams was composed entirely of university graduate students who were using the project to meet a requirement for their degree. In retrospect, making the project a class project might have worked better – a few graduate students on the team would also have helped.

Much of the team's early work was devoted to researching conditions on the moon – low gravity and its implications, terrain, geography, geology, lack of a substantial atmosphere, temperatures and sunlight at different lunar locations, etc. Research, though, quite frequently led to the conclusion that nobody knows for sure, but it is possible that… etc. Moonquakes are known, but their frequency and severity are uncertain. Meteorites are a danger in a no-atmosphere environment, but the level of danger is debatable. Because of the moon's slight angle to the ecliptic, there is a possibility of near-permanent light at higher elevations at the poles, particularly the north pole, but computer simulations cast doubt on this. Water might be obtained from ice or permafrost in deep recesses at the north pole, but this is still unknown. There might or might not be lava tubes at the north pole that could be used for protection of equipment from dust or shelter from solar events.

All of these and other unknowns are very important to a design for a lunar habitat – cushioning of the habitat, provision of a water supply, generation of energy, the importance of a decontamination facility within the habitat, etc. But in spite of these unknowns -- along with team background, time-on-task, and institutional resource limitations -- the team submitted a paper three months after starting the project, was one of three teams chosen to present at the PISCES conference, and was (from the beginning, the only community college team) voted the winner by a respected group of professionals.

The paper that the team presented was never intended to answer every question that might be asked about anything from transport by current means to the shape of interior partition corners to moon dust to the Peary Crater site that the team suggested. Rather, it was intended to introduce what the team believed was a novel concept of multiple spheres that are hard shell and by nature the strongest, most energy and materials efficient, cost effective, and easily moved forms known. Almost all of the characteristics that make them relatively unpopular as Earth habitats will not apply on the moon where there are no rectangular home sites, stores that sell rectangular building materials or square furniture, scarcity of space that requires compactness in design, or snow that might collect atop a roof that is not steeply sloped. Flat sides are inherently weak, corners impede convection and forced air flow. The rest of the universe knows what people on Earth have yet to learn – that the sphere is "nature's perfect form." In Earth habitat design we can afford to be somewhat inefficient. On the moon, though, efficiency in every respect will be critical.

The team also stressed the importance of sustainability. A habitat on the moon must be more than a space station affixed to a planetary body. We have proven that it is possible to survive in a no-atmosphere environment when supplied by everything from Earth except sunlight. A lunar habitat must have a more important mission of better preparing us for moving farther into space where travel and lifelines will be more difficult. The team's concept involves a biomass, an enclosed sanitation system, etc. The habitat is not self-sustaining, but it is a step in this very important direction. Expansion of the biomass, oxygen generation, and development of energy sources other than solar would follow. The team's habitat is intended to be a laboratory rather than a place to simply survive. Very few of the habitat designs the team has seen address this.

The hard shell is another important part of the concept. In addition to strength, it makes built-ins possible. The difficulty and end result of installing piping, wiring, and equipment in an inflatable or an unfoldable was recognized very early. In a hard shell design, as explained earlier in this paper, pipes and wiring can be hidden and out of the way. This means a safer and more efficient use of space. It also greatly reduces setup time, avoids the chance of problems during installation, and saves materials and weight.

<u>Ribbing Needed for Strength</u>

A reviewer's comment about the shell was its lack of ribs and floor support "rings." The paper that the team presented at the PISCES conference actually showed in x-ray elevations and a section of the shell a system of upright and lateral ribs (Honolulu Community College, 2007). A rectangular configuration was chosen because it worked best with the openings between the spheres and with the floor levels. A Honolulu structural engineering firm recommended 6-inch x 2-inch ribs integrated with a 1-inch composite shell. Following that recommendation, however, the composites technicians at the Marine Education and Training Center at the college came out in perfect agreement that ribs and a 1-inch shell were not needed. The team contacted an engineer at Boeing and others with composites design and fabrication experience, but received no better advice. The team preferred to proceed with the opinion of the Marine Center (certified) technicians, and the ribs were removed at the next opportunity. An 8-inch sphere wall was designed for the 26-foot sphere. As it is, the outer shell, core, and inner liner work together as a unit to provide the strength required. Ribs could be accommodated, however, if it were determined (probably by prototype construction and testing) that ribs are in fact needed.

## Rolling a Sphere Over Rough Terrain

Most comments about the sphere relate to its being rolled over possibly rough terrain. Mobility was not the principal reason for the team's spherical design. Placing the sphere is a one-time activity, and being "stuck" forever with the sphere simply because it made that one task easier would be foolish. Most importantly, strength and materials, weight, space, and energy efficiency are the reasons for the sphere. Nevertheless, if the habitat will be a hard shell, it is still the case that a sphere would be the easiest of any form to move. Most other forms need to be skidded, wheeled, or tumbled, and probably the most dangerous habitat to move over rough terrain would be a soft inflatable habitat. Possible solutions for the sphere are the following:

- Prior site preparation (needed for probably any habitat on the lunar surface). This was discussed by the team but should probably have been addressed in greater detail in the report.
- A movable mat or runway that is advanced with the sphere.
- Selection of a level site.

The team did not address this issue in length most likely because a two or three kilometer displacement was never considered. Such a distance, however, would at least favor a ready-equipped habitat that eliminates the need to transport the habitat, equipment, and supplies individually.

## The Connections Between the Spheres

There were other aspects of the design that the team would like to have had the time and in some cases the resources to work on. One was the sphere connectors mentioned by a reviewer. These were intended to be flexible to minimize the risk of damage due to moonquakes or any catastrophic event that might cause movement in one of the spheres. They could be as simple as a sturdy foamed plastic that provides both thermal insulation and flexibility. A rigid floor would attach to one sphere and be free to move back and forth at the adjacent sphere.

Extreme heat might cause problems if the connectors are foamed plastic, but temperature variations would be fairly moderate if a pole location were chosen as suggested. Weather conditions would not be an issue. Still, the team did not focus on these beyond agreeing on their requirements and understanding that their design would likely be straightforward, and different materials and configurations would also not affect the overall concept and design. The connectors need to contain flexible wiring raceways and pipes below the walkways.

Doors were another component that the team did not work on. Their design and operation, though, would be similar to those of aircraft doors that are strong, airtight, and stored at a side when open.

## Dust Considerations

A recent comment was about dust. The team was fully aware of dust conditions on the moon. In respect to dust and other material possibly carried into the habitat, the team's design was about the only one anyone saw that contained decontamination facilities. The hard shell of the habitat is also very suitable to a dusty environment. Outside of the habitat, dust is a problem in machinery. Rovers, for example, will need special protection. The adjustable struts that support the spheres also have flexible sleeves that slip over threaded and other movable parts. As prominent as dust is on the moon, there is no wind or other weather conditions that would exasperate the problem. In homes on Earth, indoor/outdoor air exchanges are typically required, but a lunar habitat will be airtight. Infiltration should be minimal.

## Why Not Partially Bury the Spheres?

The possibility of burying the bottom third of the spheres is discussed in the full report (Honolulu Community College, 2007, p. 21). The primary purpose would be that of protection from solar events in the no-atmosphere environment. The proposal is to rest the spheres on the lunar surface, possibly on a cushion similar to that built into the struts. The struts, then, would act more as braces than as load-bearing supports. Actual testing would likely determine the amount and design of support and stabilization.

The team's preliminary report submitted in July of 2007 actually had a flattened bottom on the spheres. This would provide for a greater distribution of support while not significantly interfering with the spheres being rolled into position. The flattened bottoms, however, were omitted prior to the final support in favor of more storage space possibly for batteries, flywheels, or other energy storage devices needed during extended periods of no sunlight.

Partially burying the spheres, the team believes, would be a rather extreme means of providing stability. Creating the depressions in the lunar surface, lining them, and actually getting the spheres into the depressions and at the correct rotations could be difficult. Digging could be difficult, and blasting would be difficult at any later expansion of the habitat without upsetting the spheres already in place. Site preparation prior to placement of any habitat will almost certainly be required. But an appropriate habitat design should make major pre-construction unnecessary.

Related to the idea of partially burying the spheres is the team's proposal (Honolulu Community College, 2007, p. 20) to construct an underground shelter for inhabitants soon after establishment of the habitat. This would be created from inside a sphere through a hatch in the bottom floor. It would be probably elevator size to accommodate six people for a short period of time, and it could be accessed quickly and easily on short notice of a solar event.

Size of the Plans in This Paper

Another recent comment by a reviewer was about the small size of the plans provided in the paper. They are simplified plans originally designed for a four-page section of this paper that was intended to include material from the papers presented by the other two winning teams as well as the AEC team. More detailed plans are contained in the full report at the web site address given earlier.

Some Lessons Learned

Essentially everything that forms the basis of this paper was learned during the course of work on the project. Most importantly, the students learned the value of participation, teamwork, and disciplines they had not previously seen much connection with. They had to think beyond the way things work on Earth and beyond current technologies and usual ways of thinking. As uncomfortable as it was, they realized that there were many things they did not know that they thought they knew, that they did not know many things simply because they had previously not been interested or needed to know, and that most things are more complex than they had suspected. The world of knowledge and discovery is somewhat more important and interesting as a result of the lunar habitat design project. It was an invaluable exercise in research, logic, presentation, creativity, and collaboration.

The project was also a lesson in what people can accomplish with interest, hard work, and vision. These were freshman college students with little background in space-related sciences and technologies, who made up the only community college team in the competition, did their best against big name, well-endowed, research university teams, and won.

Overall, the team's participation would have been aided by members being involved in a more closely related college program or organization of individuals with similar interests in space exploration and development as well as an existing pool of experience and knowledge. Construction and testing capabilities would also have helped. A larger industrial base in Hawaii might also have lent support.

The team always expected that further engineering would be needed to develop the habitat design, and transport capabilities would need to be improved at the same time. It seems very unlikely that delivery capabilities 20 or 30 years from now will still limit a lunar habitat to being probably an inflatable small enough and light enough to be carried to the lunar surface in a tiny lander. A two-stage transportation system that requires transfer of cargo from a large payload area to a small lander cannot be anything more than a very short and inefficient part of a solution to establish a habitat on the lunar surface. An efficient, direct, and cost effective system will inevitably be developed. One-sixth gravity and lack of weather conditions will ensure it. The capability of delivering a 24- or 26-foot sphere will be a reality – sooner or later.

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