BUILDING HABITATS ON THE MOON

Engineering Approaches to Lunar Settlements

Haym Benaroya

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To
Esther and Alfred,
my parents

About the Author

Haym Benaroya is a Professor of Mechanical and Aerospace Engineering at Rutgers University. His research interests are focused on the conceptualization and analysis of structures placed in challenging environments. These include offshore drilling structures and lunar surface structures for manned habitation.

Professor Benaroya earned his BE degree from The Cooper Union in New York, and his MS and PhD from the University of Pennsylvania in Philadelphia. Prior to joining Rutgers University in 1989, Professor Benaroya was a senior research engineer at Weidlinger Associates in New York for eight years.

While at Rutgers, Professor Benaroya has mentored twelve students to their PhDs and a similar number to their MS degrees. He is the author of over 80 refereed journal publications, two text books – one in Vibration and the other in Probabilistic Modeling – and two research monographs with two former PhD students on structural dynamics in the ocean.

His book, **From Dust to Gold - Building a Future on the Moon and Mars**, presents a vision of settling the Solar System. It was awarded the 2012 Best Engineering Sciences Book by the International Academy of Astronautics. Professor Benaroya is an elected member of the International Academy of Astronautics.

Preface

"The greatest adventure of all time."

When most of us think about the Moon, we don't really have a good sense about its size, its constituent elements, and the harshness of its environment. The Moon is truly a small body, quite a bit smaller than the Earth. Earth's total surface area is 510.1 x 10^6 km^2, with a land area of 149.8 x 10^6 km^2. This is almost four times the total lunar surface area of 37.9 x 10^6 km^2. Mars, for comparison, is about 144.8 x 10^6 km^2. Coming from Earth, humans have a certain instinct regarding how far the horizon should be, and astronauts who walked on the Moon remarked about their surprise at how close the lunar horizon seemed to them.

This is a book about the structural engineering of settlements on the lunar surface, and a bit on sublunar sites. It is about the Moon, rather than Mars, for two reasons. The first is that we know the most about the Moon. Humans have been there six times. The second reason is the Moon's proximity to Earth. Consider this: if the Earth is 100 units in diameter, the Moon is 3000 units away and is 27 units in diameter, and Mars is 428,000 units away and 53 units in diameter. The surface of Mars receives about 44 percent of the sunlight intensity that the surfaces of the Earth and Moon experience. Getting people safely to the Moon for a very long stay is barely within the abilities of our highly technological society. Some aspects are a bit beyond our abilities, but much is within that horizon of our talents. Mars, however, is another story. Much of what we need to be able to do to get people to Mars is beyond that horizon. It is not a matter of money, but rather a matter of experience in space, of surviving in space. More specifically, experience and survival on the Moon. If someone gave me as much money as I wanted to make humanity a spacefaring civilization, I would still choose the Moon as our first goal. This book will provide some insights into that choice.

We'll discuss all the issues in detail: engineering, as well as human physiology and psychology. And that is the critical difference between most engineering projects on Earth and those involving space. Human survival is part of the equation – physical survival and psychological survival. These considerations are a part of the very difficult challenge of designing habitats for humans on the Moon, or elsewhere outside of Earth's protective atmosphere.

We will approach the structural engineering in such a way that an intelligent and generally well-educated reader can follow most of the ideas that are presented. Of course, there will be points in our development where an understanding of physics and mathematics is required. While we are eager to make the material accessible to a large group of readers, we are also devoted to the creation of a book that can be used to inform the engineers that will eventually, hopefully soon, be called upon to prepare preliminary structural designs for the lunar surface.

Figure 0.1. *Earthrise* is the name given to a photograph of the Earth taken by astronaut William Anders in 1968 during the Apollo 8 mission. (Courtesy: NASA)

The material in this book could have been developed in a variety of sequences, all of which would have met their mission. That is, to provide an overview with some details about the engineering, scientific, medical, psychological, political, and economic aspects that have a role in the creation of a significant and permanent human presence on the Moon. In our effort, we first discuss the lunar environment, and how it affects humans in so many ways, because the structures designed to house them must also safeguard them against that environment. Additionally, given the indoor life awaiting the inhabitants of the Moon, we need to provide them with a psychologically pleasing and nurturing haven within which to thrive.

Of course, we discuss in great detail the design of structures primarily for the lunar surface, using ideas from the mechanics of solids, the idea of stress, strain and displacement. We detail how engineers couple material properties, structural geometry and engineering reliability to create structures that perform as desired, effectively, safely, for a prescribed amount of time. A significant list of references to the literature is provided as follow-on for the interested reader. We also include a large set of references to our own work, since we are most familiar with these. Sometimes, we are able to walk through all this a step at a time, descriptively with words and their shorthand, mathematics, while at other times the presentation is in a highlighted way, but still mentioning the key ideas. By the end, the devoted reader will have a good understanding of structural mechanics for the lunar surface, and more.

With this book, we offer the reader an appreciation of the tremendous breadth of both the intellectual and financial resources needed to embark on a manned space program to the Moon, Earth's closest body, but our focus is on the various designs proposed for safe habitats for living on the lunar surface. These designs must eventually accommodate the physiological and psychological challenges that humans will face in such environments.

A search of the literature for lunar settlements and bases will lead in the majority to the consideration of longer-term facilities that are only possible after the creation of a lunar industrial infrastructure. The key is, and has always been, how to get there (the expansive lunar bases that our mind's eye imagines will evolve over the next century or two) from here (designing and placing the first habitats, of small volume, that can house a few pioneers). At this time (late 2017), no nation or industrial entity has a program or plan to send astronauts to the Moon for permanent or semi-permanent habitation. This is not because we cannot, but because the process is long and the United States, still the preeminent space-exploring nation, does not yet see this as a high priority. Industries are making major strides, but primarily with transportation systems, with Bigelow the exception by creating a habitat. But it appears that the Moon may again be of interest to the national space programs of China, Japan, Russia, and slowly, the United States. It will happen, the question is when.

The goal of this book then is to provide an overview of lunar structural concepts, understand how they can be designed, and acknowledge the severe environmental concerns. We know that the human body and mind that has evolved for the 1 *g* radiation-free surface of the Earth over millions of years, both physically and psychologically, is not naturally suited to space without advances in medical science. Humans on the lunar surface can be protected against the radiation, the micrometeoroids and the vacuum, but the low gravity effects are, as yet, only partially understood. As structural designers working with architects and a host of other professionals, we recognize that there are numerous design constraints for a lunar structure, as compared to a typical Earth structure. Our experience base needs broadening, but we know that the first long-term manned facilities will be works in progress from which we learn much while they protect our settlers.

It is worth noting that while the actual analysis and design of lunar surface structures are, for the most part, understood from the perspectives of structural engineering, the challenges arise from the need to characterize the lunar environment, the uncertainties associated with that environment, and the environmental effects on biological entities, materials, electronics, machines and structures. There are also the serious challenges to our abilities when we try to estimate structural and system risk and reliability, which are partially related to the lunar environment and partially related to the complexity of the structural system. In a few words, once the environment is defined we can go forward with a structural analysis and design, but the uncertainties across the relevant disciplines preclude a straightforward path. Other engineering disciplines that are part of the overall design of a lunar habitat, from chemical to electrical, are not mentioned here. And they face similar challenges.

The question we ask ourselves is: What is the design problem? Can we define the problem in a way that helps us begin to solve it? The short answer is: To design a structure for the lunar surface that can safely be inhabited by humans, where they can live, work, and thrive as individuals. That goal may not initially be met in all its dimensions, but that is our goal in time.

This book is an effort to gather relevant ideas on the design of a lunar habitat. It is not, and cannot be, conclusive, or all inclusive. It is representative. Too much yet needs to be discovered and figured out for any study to be conclusive. Of the many thousands of published reports, papers and books, only a very small fraction have been referenced here. Many high-quality studies have not been referenced, with regret. The topic of this book could have led to an encyclopedia of many volumes that would still be incomplete. The reader, however, will come away with some general – and some specific – insights into the challenges that face us when we eventually decide to return to the Moon, with people who will reside there for the long term, and eventually, for some, the remainder of their lives.

As President Kennedy said in his speech at Rice University: "… we have given this program a high national priority – even though I realize that this is in some measure an act of faith and vision, for we do not now know what benefits await us …" We have some ideas of the benefits, but there are many benefits that will flow from discoveries that we cannot even imagine, so how can we imagine the second and third generation discoveries that will emanate from those that we cannot yet imagine?

The story is still in its infancy.

1

Thoughts on the Moon

"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

1.1 J.F.K. AT RICE UNIVERSITY

Address at Rice University on the Nation's Space Effort by President John F. Kennedy, Houston, Texas, September 12, 1962.

> President Pitzer, Mr. Vice President, Governor, Congressman Thomas, Senator Wiley, and Congressman Miller, Mr. Webb, Mr. Bell, scientists, distinguished guests, and ladies and gentlemen:
>
> I appreciate your president having made me an honorary visiting professor, and I will assure you that my first lecture will be very brief.
>
> I am delighted to be here and I'm particularly delighted to be here on this occasion.
>
> We meet at a college noted for knowledge, in a city noted for progress, in a State noted for strength, and we stand in need of all three, for we meet in an hour of change and challenge, in a decade of hope and fear, in an age of both knowledge and ignorance. The greater our knowledge increases, the greater our ignorance unfolds.
>
> Despite the striking fact that most of the scientists that the world has ever known are alive and working today, despite the fact that this Nation's own scientific manpower is doubling every 12 years in a rate of growth more than three times that of our population as a whole, despite that, the vast stretches of the unknown and the unanswered and the unfinished still far outstrip our collective comprehension.
>
> No man can fully grasp how far and how fast we have come, but condense, if you will, the 50,000 years of man's recorded history in a time span of but a half a century. Stated in these terms, we know very little about the first 40 years, except at the end of

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them advanced man had learned to use the skins of animals to cover them. Then about 10 years ago, under this standard, man emerged from his caves to construct other kinds of shelter. Only five years ago man learned to write and use a cart with wheels. Christianity began less than two years ago. The printing press came this year, and then less than two months ago, during this whole 50-year span of human history, the steam engine provided a new source of power.

Newton explored the meaning of gravity. Last month electric lights and telephones and automobiles and airplanes became available. Only last week did we develop penicillin and television and nuclear power, and now if America's new spacecraft succeeds in reaching Venus, we will have literally reached the stars before midnight tonight.

Figure 1.1. Attorney General Kennedy, McGeorge Bundy, Vice President Johnson, Arthur Schlesinger, Admiral Arleigh Burke, President Kennedy, Mrs. Kennedy watching the 15-minute historic flight of astronaut Alan Shepard on television, May 5, 1961, the first American in space. (Cecil Stoughton, photographer. Courtesy John Fitzgerald Kennedy Library, Boston, MA)

This is a breathtaking pace, and such a pace cannot help but create new ills as it dispels old, new ignorance, new problems, new dangers. Surely the opening vistas of space promise high costs and hardships, as well as high reward.

So it is not surprising that some would have us stay where we are a little longer to rest, to wait. But this city of Houston, this State of Texas, this country of the United States was not built by those who waited and rested and wished to look behind them. This country was conquered by those who moved forward – and so will space.

William Bradford, speaking in 1630 of the founding of the Plymouth Bay Colony, said that all great and honorable actions are accompanied with great difficulties, and both must be enterprised and overcome with answerable courage.

If this capsule history of our progress teaches us anything, it is that man, in his quest for knowledge and progress, is determined and cannot be deterred. The exploration of space will go ahead, whether we join in it or not, and it is one of the great adventures of all time, and no nation which expects to be the leader of other nations can expect to stay behind in this race for space.

Those who came before us made certain that this country rode the first waves of the industrial revolutions, the first waves of modern invention, and the first wave of nuclear power, and this generation does not intend to founder in the backwash of the coming age of space. We mean to be a part of it – we mean to lead it. For the eyes of the world now look into space, to the moon and to the planets beyond, and we have vowed that we shall not see it governed by a hostile flag of conquest, but by a banner of freedom and peace. We have vowed that we shall not see space filled with weapons of mass destruction, but with instruments of knowledge and understanding.

Yet the vows of this Nation can only be fulfilled if we in this Nation are first, and therefore, we intend to be first. In short, our leadership in science and in industry, our hopes for peace and security, our obligations to ourselves as well as others, all require us to make this effort, to solve these mysteries, to solve them for the good of all men, and to become the world's leading space-faring nation.

We set sail on this new sea because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people. For space science, like nuclear science and all technology, has no conscience of its own. Whether it will become a force for good or ill depends on man, and only if the United States occupies a position of pre-eminence can we help decide whether this new ocean will be a sea of peace or a new terrifying theater of war. I do not say that we should or will go unprotected against the hostile misuse of space any more than we go unprotected against the hostile use of land or sea, but I do say that space can be explored and mastered without feeding the fires of war, without repeating the mistakes that man has made in extending his writ around this globe of ours.

There is no strife, no prejudice, no national conflict in outer space as yet. Its hazards are hostile to us all. Its conquest deserves the best of all mankind, and its opportunity for peaceful cooperation many never come again. But why, some say, the moon? Why choose this as our goal? And they may well ask why climb the highest mountain? Why, 35 years ago, fly the Atlantic? Why does Rice play Texas?

We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.

It is for these reasons that I regard the decision last year to shift our efforts in space from low to high gear as among the most important decisions that will be made during my incumbency in the office of the Presidency.

In the last 24 hours we have seen facilities now being created for the greatest and most complex exploration in man's history. We have felt the ground shake and the air shattered by the testing of a Saturn C-1 booster rocket, many times as powerful as the Atlas which launched John Glenn, generating power equivalent to 10,000 automobiles with their accelerators on the floor. We have seen the site where five F-1 rocket engines, each one as powerful as all eight engines of the Saturn combined, will be clustered together to make the advanced Saturn missile, assembled in a new building to be built at Cape Canaveral as tall as a 48 story structure, as wide as a city block, and as long as two lengths of this field.

Within these last 19 months at least 45 satellites have circled the Earth. Some 40 of them were made in the United States of America and they were far more sophisticated and supplied far more knowledge to the people of the world than those of the Soviet Union.

The Mariner spacecraft now on its way to Venus is the most intricate instrument in the history of space science. The accuracy of that shot is comparable to firing a missile from Cape Canaveral and dropping it in this stadium between the 40-yard lines.

Transit satellites are helping our ships at sea to steer a safer course. Tiros satellites have given us unprecedented warnings of hurricanes and storms, and will do the same for forest fires and icebergs.

We have had our failures, but so have others, even if they do not admit them. And they may be less public.

To be sure, we are behind, and will be behind for some time in manned flight. But we do not intend to stay behind, and in this decade, we shall make up and move ahead.

The growth of our science and education will be enriched by new knowledge of our universe and environment, by new techniques of learning and mapping and observation, by new tools and computers for industry, medicine, the home as well as the school. Technical institutions, such as Rice, will reap the harvest of these gains.

And finally, the space effort itself, while still in its infancy, has already created a great number of new companies, and tens of thousands of new jobs. Space and related industries are generating new demands in investment and skilled personnel, and this city and this State, and this region, will share greatly in this growth. What was once the furthest outpost on the old frontier of the West will be the furthest outpost on the new frontier of science and space. Houston, your City of Houston, with its Manned Spacecraft Center, will become the heart of a large scientific and engineering community. During the next 5 years, the National Aeronautics and Space Administration expects to double the number of scientists and engineers in this area; to increase its outlays for salaries and expenses to $60 million a year; to invest some $200 million in plant and laboratory facilities; and to direct or contract for new space efforts over $1 billion from this Center in this City.

To be sure, all this costs us all a good deal of money. This year's space budget is three times what it was in January 1961, and it is greater than the space budget of the

Figure 1.2. *From the Earth to the Moon* (French: *De La Terre à la Lune,* 1865) is a humorous science fantasy novel by Jules Verne and is one of the earliest entries in that genre. It tells the story of a Frenchman and two well-to-do members of a post-American Civil War gun club who build an enormous sky-facing cannon, the *Columbiad*, and launch themselves in a projectile/spaceship from it to a Moon landing.

previous eight years combined. That budget now stands at $5400 million a year – a staggering sum, though somewhat less than we pay for cigarettes and cigars every year. Space expenditures will soon rise some more, from 40 cents per person per week to more than 50 cents a week for every man, woman and child in the United States, for we have given this program a high national priority – even though I realize that this is in some measure an act of faith and vision, for we do not now know what benefits await us. But if I were to say, my fellow citizens, that we shall send to the moon, 240,000 miles away from the control station in Houston, a giant rocket more than 300 feet tall, the length of this football field, made of new metal alloys, some of which have not yet been invented, capable of standing heat and stresses several times more than have ever been experienced, fitted together with a precision better than the finest watch, carrying all the equipment needed for propulsion, guidance, control, communications, food and survival, on an untried mission, to an unknown celestial body, and then return it safely to Earth, re-entering the atmosphere at speeds of over 25,000 miles per hour, causing heat about half that of the temperature of the sun – almost as hot as it is here today – and do all this, and do it right, and do it first before this decade is out – then we must be bold.

I'm the one who is doing all the work, so we just want you to stay cool for a minute. [laughter].

However, I think we're going to do it, and I think that we must pay what needs to be paid. I don't think we ought to waste any money, but I think we ought to do the job. And this will be done in the decade of the sixties. It may be done while some of you are still here at school at this college and university. It will be done during the terms of office of some of the people who sit here on this platform. But it will be done. And it will be done before the end of this decade.

And I am delighted that this university is playing a part in putting a man on the moon as part of a great national effort of the United States of America.

Many years ago, the great British explorer George Mallory, who was to die on Mount Everest, was asked why did he want to climb it. He said, "Because it is there."

Well, space is there, and we're going to climb it, and the moon and the planets are there, and new hopes for knowledge and peace are there. And, therefore, as we set sail we ask God's blessing on the most hazardous and dangerous and greatest adventure on which man has ever embarked.

Thank you.

1.2 EDWARD TELLER: THOUGHTS ON A LUNAR BASE

"The Moon can be a nascent civilization."

I would like to start with a statement that I expect, and even hope, may be controversial.(1) I believe there is a very great difference between the space station now being planned and any activity on the Moon now under discussion. I believe that in the space station we should do as much as possible with robots for two simple reasons. There is nothing in space—practically nothing—except what we put there. Therefore, we can foresee the conditions under which we are going to work, and, in general, I think robots are less trouble than people.

The other reason is that, apart from experiments and special missions that we have in space, we do not want to proceed to change anything in space, whereas on the Moon we will want to change things. Likewise, on the Moon, we will find many things that we do not expect. Adapting robots to all the various tasks that may come up, and that we do not even foresee, is not possible.

The space station is obviously extremely interesting for many reasons. However, that is not what I want to talk about except to state that, of course, the space station is apt to develop into a transfer station to the Moon. Therefore, its establishment is not independent of what we are discussing here.

I would like to look forward to an early lunar colony. I do not want to spend time in making estimates but simply want to say that it would be nice to have a dozen people on the Moon as soon as possible. I think we could have it in ten years or so. When I say 12 people, I do not mean 12 people to stay there but to have 12 people at all times, to serve as long as it seems reasonable. To me, three months is the kind of period from which you could expect a good payoff for having made the trip. Longer rotations than that might be a little hard, and efficiency might come down. But all this is, of course, a wild estimate on my part.

What kind of people should be there? It will be necessary to have all of them highly capable in a technical manner, and I believe that they should perform all kinds of work. Probably at least half of them, after coming back to Earth, should get the Nobel Prize. The result will be that we will soon run out of Nobel Prizes because I believe there will be very considerable discoveries.

Also, if you have 12 people you probably ought to have a Governor. I have already picked out the Governor to be, of course, Jack Schmitt. Furthermore, I would like to tell you that when I first testified about space, and was asked whether there should be women astronauts, I proposed that all astronauts should be women. The packaging of intelligence in women is more effective in terms of intelligence per unit weight. However, in view of the strong sentiment for ERA, I think I might compromise with an equal number of women and men. That arrangement has all kinds of advantages.

I believe that the discussion here has had plenty of emphasis on what I know will be the main practical result of a lunar base — use as a refueling station. It will supply both portable energy in a concentrated form and portable fuel for refueling rockets, primarily in the form of oxygen extracted out of lunar rocks. The only question is how to do it. My first idea was, of course, we should do it with nuclear reactors. Perhaps the environmental movement, the Sierra Club, may not have an arm that extends beyond one light second. On the other hand, we will have some problems, problems of cooling. However, most of the energy might be needed to squeeze oxygen out of iron oxide, and that simply means a high temperature. You may not need a lot of machinery, and some of the energy can be, in this way, usefully absorbed right inside the reactor. What remains probably should be converted to electricity.

The other possibility is solar energy. I am strongly inclined to believe that solar energy will be quite useful for two reasons. First, great advances have been made in solar cells, particularly with regard to Ovshinsk's idea of utilizing amorphous semiconductors. The point is that they are not very good conductors of electricity and therefore must be thin, but, on the other hand, amorphous materials are very good absorbers of light and therefore can be thin. Methods to fabricate them have indicated that you can, with practical certainty, get down to one dollar per peak watt.

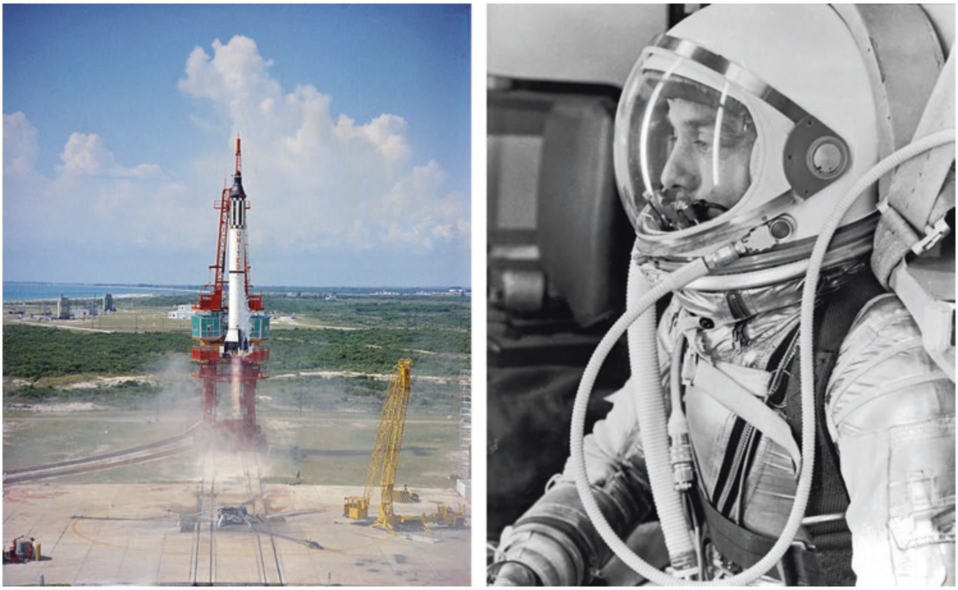

Figure 1.3. (Left) Launching of the Mercury-Redstone 3 rocket from Cape Canaveral on astronaut Alan B. Shepard's Freedom 7 suborbital mission. NASA research mathematician Katherine Johnson did the trajectory analysis for the mission, America's first human spaceflight. (Right) Shepard, in his silver pressure suit with the helmet visor closed, prepares for his launch on May 5, 1961. Shepard's capsule lifted off at 9:34 a.m. from Launch Complex 5 at Cape Canaveral Air Force Station, and flew a suborbital trajectory lasting 15 minutes and 22 seconds. During the rocket's acceleration, Shepard was subjected to 6.3 *g* just before shutdown of the Redstone engine, two minutes and 22 seconds after liftoff. Soon after, America's first space traveler got his first view of the Earth. "What a beautiful view," Shepard said. His spacecraft splashed down in the Atlantic Ocean, 302 miles from Cape Canaveral, where he and Freedom 7 were recovered by helicopter and transported to the awaiting aircraft carrier USS Lake Champlain. (Courtesy: NASA)

There is, however, another advantage to solar power and that is if you do not want power, but just want high temperature for driving oxygen out of oxides, you may not need mirrors that have to be moved. It might be sufficient to have the right kind of surface that absorbs and emits ultraviolet but is highly reflective in the visible and the infrared. In equilibrium with solar radiation, this will give high temperatures; the farther you go in the ultraviolet the more you can approach the maximum temperature obtainable, the surface temperature of the Sun. If you try to approach this limit, then the energy content — the power — will be small because it utilizes a smaller portion of the solar spectrum. But the temperature you can get is high. What the optimum is where you will want to compromise, I do not know.

Let me extend this idea one step further. I would not only like to get very high temperatures; I also want to get very low temperatures as cheaply as possible. You can achieve the latter during the 14-day lunar night. If you isolate yourself from the surface of the Moon, put your apparatus on legs and put some space in between — all very cheap arrangements — you can approach temperatures in the neighborhood of 2.7 degrees Absolute. In this way, you can get low temperature regions of large volume and high temperature regions of large volume.

Now, I would like to talk about one practical point that may not have been discussed, namely, the question of where on the Moon the colony should be. I would like to go to one of the poles because I would like to have the choice between sunlight and shade with little movement. Furthermore, it would be a real advantage to establish the colony in and around a crater where you might have even permanent shade in some places and where moving away from the rim on one side or the other you can vary conditions quite fast. Of course, it is of importance not only to position yourself in regard to the Sun but also in regard to the Earth. For many purposes, you want to see the Earth in order to observe it. For other purposes, for instance astronomy, you want to be shielded from the Earth, not to be disturbed by all the terrestrial radio emission. All these conditions will be best satisfied in a crater near a pole.

I have a little difficulty in reading the lunar maps. There seem to be three good craters in the immediate vicinity of the south pole but no good craters near the north pole, or vice versa I am not quite sure. At any rate, I want to go to the pole that has the craters.

The purpose of all this is obviously what I have said to begin with and what you all realize — refueling and energy. Oxygen is the main point, but it would be nice also to have hydrogen. Hydrogen we could get from the Earth much more cheaply than the oxygen, but still it is one-ninth the cost of oxygen plus the considerable weight of the tank. Hydrogen has been deposited in the lunar dust by the solar wind over geologic time, and the mass of hydrogen in that lunar dust, as far as I know, is not much less than one part in ten thousand. Without having made a decent analysis, my hunch is that it is easier to move the lunar dust a few miles on the Moon than to come all the way from the Earth even though you have to move ten thousand times the mass. If you can distill oxygen out of iron oxide, you certainly can distill hydrogen out of the lunar dust. Furthermore, Jack Schmitt tells me that there is a possibility of finding hydrogen, perhaps even hydrogen that is four and one-half billion years old, in other parts of the Moon in greater abundance than what we see in the average lunar dust.

All of this is, of course, of great importance and perhaps serves as a little illustration of what kind of constructions we are discussing. Obviously, we will have to try to make these constructions with tools as light as can be transported from the Earth. In planning the lunar colony, special tools and special apparatus have to be fabricated on the Earth, specifically adapted to the tasks already described as well as others.

I would like to make a special proposal. I believe that surveillance of the Earth — permanent, continuous surveillance that is hard to interfere with — is an extremely important question; important to us, important for the international community, important for peace keeping. There have been proposals, and I am for them, to guarantee present observation of facilities by treaties. On the other hand, treaties not only can be broken; treaties have been broken. It is in everyone's best interest to have observation stations that are not easy to interfere with.

I would like to take the biggest chunks that I could get off the Moon and put them into a lunar orbit, perhaps 120 and 240 degrees away from the Moon. Of course, they will be very small compared to the Moon but maybe quite big compared to other objects that we put into space. If the Moon and these two additional satellites are available for observation, then we can have a continuous watch on all of the Earth with somewhat lesser information around the pole. The latter also can be obtained with additional expenditure, but to have 95 percent of the most interesting part of the Earth covered continuously would be already a great advantage. I would be very happy if, on these observation stations, we would do what we should have done with our satellites and are still not doing, namely, make the information of just the photographs obtained from the satellites universally available. I believe that would be a great step forward in international cooperation, international relations, and peace keeping.

Traveling to these artificial satellites from the Moon is a much smaller job than reaching them from the Earth. Since you stay on the same orbit, you just have to have a very small additional velocity after leaving the Moon, wait until you are in the right position, and then use a retrorocket. The total energy for that is small, and if you produce the rocket fuel on the Moon, then I think you have optimal conditions.

I also would like to have a satellite with a special property. It should have as big a mass as possible, built up from a small mass in the course of time. But, furthermore, I want it to rotate in such a manner that instead of turning the same face all the time to the Earth it should turn the same face all the time to the Sun. If you can do that, then half of the surface will be in permanent night, half in permanent illumination, and whatever we can do on the Moon, for instance setting up a permanent low-temperature establishment, you can do that very much better on these satellites.

Now, I would like to finish up by making a very few remarks on purely scientific work that will become possible. In the vacuum of the Moon we can work with clean surfaces. It is obvious that surface chemistry could make big strides. This can be done equally well in the space station, and, in this respect, the Moon does not have an obvious advantage.

Where you do get an obvious advantage is in astronomical observations where you want the possibility to collimate in a realty effective manner. When you want to look at *X*-rays or gamma rays from certain directions, all you need to do is to drill a deep hole that acts as a collimator and have the detectors at its bottom. You would have to have a considerable number of these holes, but I believe that it will be much cheaper than to have a considerable number of observation apparatus shot out from the Earth, particularly because the mass for collimation will be not available in space stations except at a considerable cost. The same holes may be used for high energy cosmic rays.

Another obvious application is in high-energy physics. As the size of accelerators kept going up, many years ago our very good friend Enrico Fermi, at a Physical Society meeting as far as I know, made the proposal in completely serious Italian style that sooner or later we will make an accelerator around the equator of the Earth. Well, we are approaching that — at least we are planning an accelerator that takes in a good part of Texas. I am not quite sure that we should do that. Let us wait until we get to the Moon. (That might happen almost as soon as a giant accelerator can be constructed.) We actually could have an accelerator around the equator of the Moon. Taking advantage of the vacuum available, you only need the deflecting magnets and the accelerating stations, and these can be put point for point rather than continuously.

I have been interested for many years in the remarkable discovery of Klebesadel at Los Alamos of gamma ray bursts that last for longer than 15 milliseconds and less than 100 seconds, have their main energy emission between 100 and 200 kilovolts, but seem to have components far above a million volts, too. I believe everybody is in agreement that these come from something hitting neutron stars and converting the energy into gamma rays. But most people believe that they come from nearby regions of our galaxy and are, therefore, isotropic. Actually, the number of observations depends on the intensity in such way as though from more distant places we do not get as many as expected. The usual explanation is that we get these from farther places and we get them only from the galactic disc rather than a sphere. Unfortunately, these bursts are so weak that the directional determinations cannot be made. On the Moon, you could deploy acres of gamma ray detectors of various kinds and leave them exposed to the gamma rays or cover them up with one gram per square centimeter, five grams per square centimeter, or ten grams per square centimeter so that with some spectral discrimination you will get a greater intensity from perpendicular incidence than from oblique incidence. As this apparatus will look into the plane of the galaxy, into the main extension of the galaxy, or toward the galactic pole, you should see a difference, a deviation from spherical distribution, for these weakest bursts, essentially bursts of 10^{-5} to 10^{-7} ergs/cm^2/s.

A very good friend, Montgomery Johnson (who unfortunately died a few months ago) and I had made an assumption that these radiations really do not come from the galaxy but from outer space, from regions where the stars are dense and where collisions between neutron stars and dense stars like the white dwarfs may occur. Good candidates are the globular clusters, but there may be other dense regions in the universe as well. If this hypothesis turns out to be correct, then the reason you find fewer events at great distances are cosmological reasons—curvature of space, a greater red-shift, lesser numbers of neutron stars and white dwarfs in the distant past, which was closer to the beginning of the universe. Actually, if this hypothesis is correct, then the gamma-ray bursts would, in the end, give us information about early stages of the universe. No matter which way it goes, the gamma-ray bursts are interesting phenomena, and the Moon is one of the places where they could be investigated with real success.

I am sure that in these ways and many others an early lunar colony would be of great advantage.

Reference

1. Teller, E., *Thoughts on a Lunar Base*, **1985 Lunar Base Conference**, Lunar and Planetary Institute, reproduced courtesy LPI. Teller was at the Lawrence Livermore Laboratories, University of California, Livermore, CA at the time of this keynote lecture.

2

Overview and context

> *"So what did we get in return?*
> *… So much!"*

2.1 WHY THE MOON, AND HOW

The case for the permanent manned return to the Moon – as a destination in its own right, and as a platform for the human and robotic exploration of the Solar System – is clear.(1)

Great societies and civilizations advance in evolutionary ways, as well as revolutionary ways. Positive revolutionary progress can be categorized as social and technological. Social progress advances personal freedoms and opportunities. Technological progress advances the power of the individual and groups of individuals, and potentially also personal freedoms and opportunities, although such advances can also be used to repress and intimidate.

The Moon is our closest planetary body, roughly three days' flying time away, with almost instantaneous communication with Earth. The rival Mars is essentially as hostile to human life as the Moon, but also requires about a year of travel time from Earth, with a significant communications delay. A strategic view of space exploration and settlement places the Moon and Mars in their proper order, based on their proximity to Earth.

While space activities during the Apollo program of the 1960s were purely a government-led effort supported by American industrial might, today we see the beginnings of a transition, where commercial interests are staking claims to the space economic sector beyond the needs of the government. This is evident in the emerging space tourism market, commercial launch systems that service the government and private sectors, resource recovery plans via asteroid mining and sample return from the Moon, and privately financed space-based science.

Without a doubt, governments are still the largest customers. This will change as launch costs decrease, a space/lunar infrastructure is created, space resources become more valuable, and the space/lunar environment becomes critical for certain types of manufacturing and processing.

H. Benaroya, *Building Habitats on the Moon*, Springer Praxis Books,
https://doi.org/10.1007/978-3-319-68244-0_2

Far from being a barren wasteland, the Moon has a regolith composed of many of the elements needed to build an infrastructure for human activity. Hydrogen, oxygen, silicon, magnesium and, it is strongly believed, water in ice form are found in the lunar regolith. Solar power can be viable on the Moon with its two weeks of daylight per month, and the solar panels could be manufactured on site using local resource silicon. Ideas for vast solar farms embedded on the surface of the Moon have been suggested. Significant quantities of helium-3 can be tapped as nonradioactive nuclear fusion reactors become feasible as a source of power.

With the current revolution in 3D manufacturing technologies, we can envision sending robots to the Moon, in advance of people, to begin to build fully functional structures for habitation and to mine the regolith for the above-mentioned elements. Even today, such advanced manufacturing can create objects of significant complexity using multiple materials. In-situ resource utilization (ISRU), coupled with advanced robotic manufacturing capabilities, implies that our lunar facilities will be almost autonomous, with full self-repair capabilities.

Figure 2.1. The Arabian Peninsula can be seen at the northeastern edge of Africa. The large island off the coast of Africa is Madagascar. The Asian mainland is on the horizon toward the northeast. This photograph is known as *The Blue Marble*, and was taken on December 7, 1972 at a distance of about 29,000 km (18,000 miles) as Apollo 17 was heading to the Moon. NASA officially credits this photo to all three astronauts, Eugene Cernan, Ronald Evans and Harrison Schmitt. Some credit Harrison Schmitt as the photographer. (Courtesy NASA)

The challenges and risks are significant, however. There are gaps in our knowledge of how to keep humans alive and robust in the space environment in general and on the Moon in particular. Engineering reliable hardware and software for long lives in the harsh space and lunar environments also requires the solution of a number of difficult technological problems.

But we need to keep in mind that the health and engineering issues that existed on the day President John F. Kennedy gave his speech challenging the United States to send man to the Moon before the end of the decade were even more difficult than those we face today. We did not know what many of the problems were, much less how to solve them. We had the faith, though, that with a sizable, sustained effort we would be able to match the challenges. And we did.

What did we get in return? We landed men on the Moon. On a political level, the nation demonstrated its engineering and scientific superpower status. To paraphrase Kennedy, the United States was able to marshal tremendous intellectual and material resources in a short period of time to solve a problem that only a few years before was deemed beyond humanity's reach. The space race born of the Cold War gave birth to a very long list of technologies, resulting in numerous industries that gave impetus to our economy and from which we benefit to this day. Included in this bounty are the medical sciences and technologies that we depend on, as well as the rarely mentioned ability to manage super-large projects of tremendous intricacies and logistical challenges.

What do we need in order to return people to the Moon with an eye toward permanence? We need to be able to send mass to the Moon, of course, but the strategic vision requires us very quickly to be able to use local lunar resources to cover most of our needs. In-situ resource utilization will allow us to use lunar materials to build structures, manufacture very large solar panels for energy, and extract valuable elements from the lunar regolith that can be used to create an industrial infrastructure. This capability, and advanced manufacturing techniques – also known as 3D printing technologies – are the keys to a viable manned exploration and settlement effort.

In order to advance the mission outlined above, we will need the following: access to orbit; low Earth orbital operations; human-rated transportation to the Moon along with all the technologies for descent and landing; lunar habitats; solar, battery and nuclear power systems; life-support and shielding systems to safeguard against radiation, micrometeorites, and zero- and one-sixth gravity; the ability to perform surface missions; in-situ resource utilization in conjunction with necessary logistics and technologies; and fuel to ascend into lunar orbit for a return to Earth. We will need to be able to ameliorate the adverse psychological effects of close-quarters cohabitation and isolation from Earth and family. Supporting human life requires a number of additional basic capabilities – in particular, plant growth in a closed and reduced gravity environment, waste processing and nutrient recovery, atmosphere revitalization and water management. Engineering challenges include propulsion, power, structures, optics, instrumentation, environmental controls, guidance and control, data management and storage, and communications. And more.

These are all difficult challenges. Research and development will solve these problems and, as a bonus, lead to tremendous advances in engineering, medical sciences and technologies. It is not possible to predict all of these spinoffs to the Earth economies, but the history of Apollo, which contributed to the advancement of many sectors of the U.S. economy and gave birth to many more, gives us reasonable credibility when we say that we expect many advances that will feed into the Earth economy.

Clearly, the human settlement of the Moon implies the support of robots and automated systems. Research is progressing rapidly in these disciplines, but even the most advanced robots today cannot autonomously explore and build on the Moon. They require human guidance and participation.

A lunar base will first be an engineering and medical laboratory, for the study of extraterrestrial infrastructure development and for the creation of a safe environment for human habitation. Access to lunar resources will drive industrial activity. Public interest in space travel will also develop as it has today for tours of low Earth orbit. Second, it will be a site for the scientific study of the Moon and the Solar System.

In conjunction with these, the Moon will become an economic nodal point that will support space transportation in cislunar space, and outward to Mars and the asteroids and outer planets. Resources recovered on the Moon will be used to support the manufacture of items needed locally, as well as of use beyond the Moon.

Culturally, humans will evolve in other ways as well. Some predict that in a matter of a few generations, the human species will bifurcate as a result of exposure to the lunar environment. We can be certain that there is no turning back from spacefaring, and the positive feedback to life on Earth.

Why the Moon, and how – addendum

We periodically return to the onset of humanity's return to the Moon. United States administrations change every four to eight years, and with new administrations, space policies and goals go through discontinuities that have been generally painful and costly. Looking back at 1989, 1993, 2001, 2009, and now 2017, we are again at the beginning of choices to be made about space generally, and the Moon particularly. What were some of the views?

A 1992 study known as the Exploration Task Force Study concluded the following about President G.H.W. Bush's Space Exploration Initiative:(2)

> "NASA's research in strong, light-weight metal alloys and plastics will support the efforts of such industries as car manufacturing, residential and commercial construction, and aircraft manufacturing. Miniaturization of electronic components will allow future designers to downsize many electronic systems. Sophisticated, portable, light-weight, health-monitoring and medical care equipment ... will become available in emergencies, at remote locations, and for local first aid squads. Long duration space missions will require partially closed life support systems in which air, water, and food must be conserved and recirculated, which could lead to advanced air purification devices for industry and medicine, water purification equipment for homes and industry, and vital new dietary information. Software ... can help manage terrestrial hazardous materials and waste. Automation and robotics ... can be applied to automobile assembly, undersea research, robotic manipulators, and vision systems. [The requirement for] high output, low weight, portable power supplies ... may yield a portable energy source for scientific, industrial, and military outposts at remote sites on Earth. Advances in the energy industry [may result], reducing our dependency on fossil fuels. In short, ... our lives [can be made] more comfortable and our environment more secure."