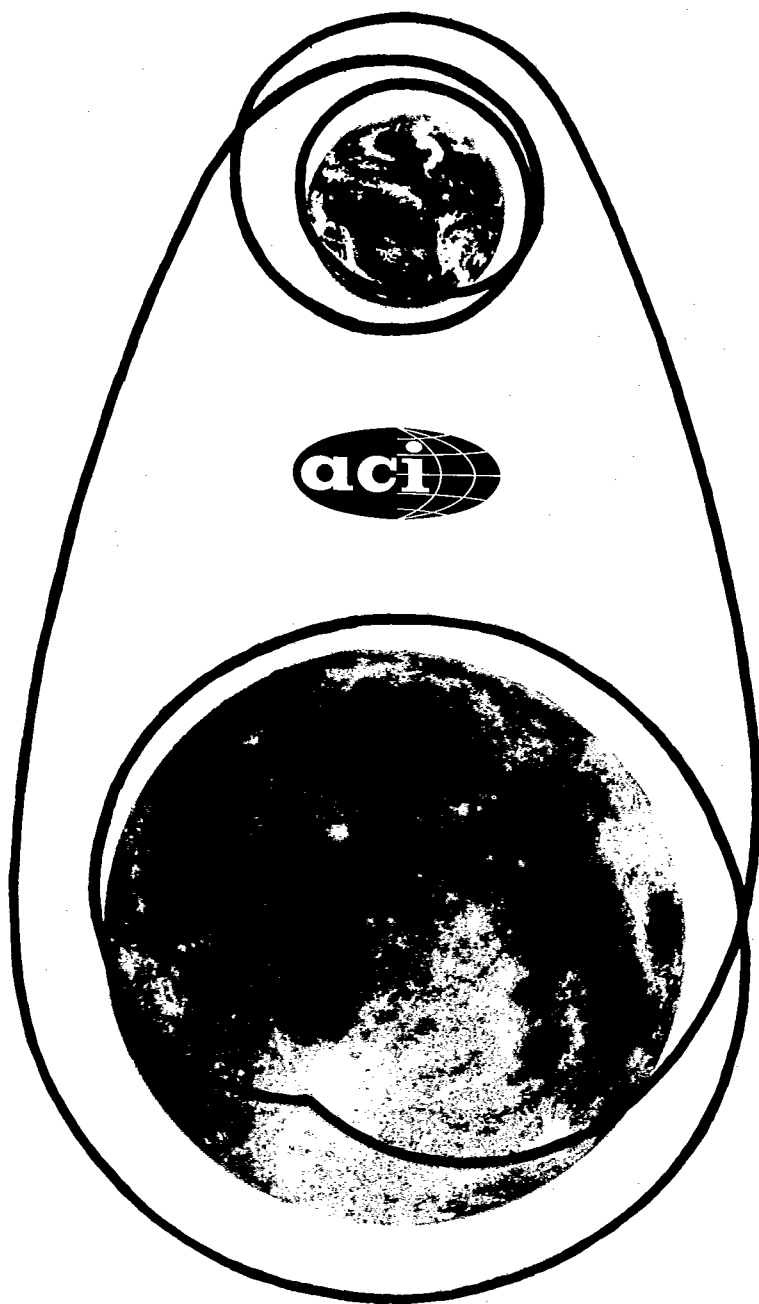


Lunar Concrete



Richard A. Kaden
Editor

Lunar Concrete



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PREFACE

That concrete might become a primary material of construction, versatile, and inexpensive for use on the Moon, would at first seem to be an outrageous idea. After all, the Moon is naturally a very dry place, drier than the driest terrestrial desert, with the nearest water hole 250,000 miles away, and the Moon's surface is enveloped in an almost perfect vacuum. This is an unfamiliar environment for the production and use of a water-containing material like concrete.

However, a small group of scientists and engineers, many of them represented in this collection of papers, have persevered in examining the outrageous premise, and perhaps the idea is not as strange as it might have initially seemed. Most, perhaps all, of the materials needed to make concrete are naturally present on the lunar surface. Although they have to be extracted and transformed, the energy required to do that, and probably the cost, is much less than that which would be required to bring the same quantity of material from Earth to use on the Moon. And the technology for utilizing these natural materials of the Moon would appear to be straightforward modifications of techniques that have been developed for terrestrial applications. It is that technology modification and adaptation to the lunar environment that is the subject of these papers.

But the development of lunar concrete into a viable material to be used on the Moon is of much broader importance than just an interesting study in technology modification and application. It is a paradigm for the Space Exploration Initiative, a bold announcement made by President George Bush on July 20th, 1989, that the U.S. would return to the Moon, "this time to stay." The lunar concrete development represents a challenge to conventional thinking, both on Earth and for Space. That challenge will excite a few young students who might otherwise have taken non-technical directions in their life to work in civil or chemical engineering, to break new and unique ground as they apply their intellect to these new problems. And in space, the traditional approaches of engineering space habitats will likewise be challenged by a new generation of engineers and

scientists, who will have more tools to work with than their predecessors. And this is only one small area of technical practice. Multiplied by the many disciplines that will need to be involved in the Space Exploration Initiative, the challenge of the Moon, and Mars, will energize a new generation of young people to think new thoughts and achieve greater heights than did the previous generation.

The papers contained in this volume are only initial steps in the process of understanding whether to use concrete on the Moon can fulfill the promise of decoupling the Moon from the Earth, moving the mine, mill, and water hole 250,000 miles up and out of the Earth's gravity well, and freeing a lunar outpost from dependence on the Earth for its construction materials. However, they are essential to the process, and are laying the basis for much more work that will certainly follow.

Michael B. Duke
Lunar and Mars Exploration Program Office
National Aeronautics and Space Administration
Houston, Texas

August 23, 1990

FOREWORD

The mission of the ACI 125 Committee is to develop and correlate knowledge and formulate recommendations for concrete construction on the Moon. This symposium volume contains the first series of papers dealing with the topic. The papers address cement production, concrete mixes, structural concepts, concrete placement, and the lunar environment.

Man's earlier exploration of the Moon during the Apollo program involved brief sorties from the flight vehicle, which served as the astronaut's lunar habitat. One of the objectives of the Space Exploration Initiative (SEI) is to establish permanent outposts on the Moon. These outposts will require permanent facilities. Ideally, these facilities can be constructed with maximum utilization of indigenous materials, such as lunar concrete.

The American Concrete Institute, through its 125 Committee, encourages the study of topics that will assist in the development of lunar concrete application in support of SEI. I hope you find this volume to be both challenging and interesting, perhaps kindling an interest in a lunar concrete study of your own.

Richard A. Kaden
ACI Committee 125, Lunar Concrete
Symposium Editor

COMMITTEE CHAIRMAN'S REMARKS

The development of worldwide space programs could not have proceeded thus far without the participation of certain elements of concrete engineering, which have not traditionally been encompassed by the aerospace industries. Although concrete professionals have never been in the front line of aerospace development, they have played key roles in construction of ground support facilities for most of the existing space programs.

In response to the Lunar/Mars initiative announced by President Bush, the National Aeronautics and Space Administration (NASA) established a Lunar/Mars Program Office in March 1990 to coordinate strategies for building bases on the Moon and ultimately, a journey to Mars in the early 21st century. The proposed lunar base cannot be practical without construction of facilities for habitats, resource processing, storage tanks, lunar surface transportation support systems, launching pads, and others.

Manned bases on the Moon will require structural materials capable of resisting a differential pressure of one atmosphere, solar wind, micro-meteoroids, and temperature extremes. Small structures for outposts envisioned for the early stage of lunar development may be fabricated on Earth and subsequently transported to the Moon. But, large structures suitable for industrial operations must be constructed using in situ lunar materials. A potential material for such construction is concrete because of its capability to resist the harsh lunar environment, and because it can be produced from lunar materials, with the exception of hydrogen for water production.

Two viable formulations for cements using simulated lunar anorthite and basalt have been developed in 1990. Paste cubes made with these new cements developed compressive strengths of 39 MPa (5,500 psi) and 49 MPa (7,100 psi), respectively.

Previous tests performed on mortar cubes made with Apollo 16 lunar soil exhibited compressive strength in excess of 75 MPa (10,000 psi).

An ongoing investigation on a dry-mix/steam-injection concreting procedure in a vacuum environment may provide a practical solution for the casting of concrete on the Moon. All of this fundamental research has been and is currently being carried out by members of American Concrete Institute (ACI) under NASA sponsorships.

It is expected that as the aerospace industry begins to examine these new opportunities, concrete, for its versatility, may become the most technically and economically feasible material for construction in space. The inclusion of concrete in space programs will broaden the constituent base of the concrete industry and add new dimensions to ACI.

Now is the time for the concrete industry to be actively involved with space programs. The newly established Lunar Concrete Committee (ACI-125) signifies the commitment of ACI to join with the aerospace industry in the development of new technologies to meet new challenges of the 21st century.

At the request of the Steering Committee of the Lunar Concrete Committee, Mr. Richard Kaden has accepted the responsibility of organizing the symposium and compiling this symposium volume, which he has carried out alone on a voluntary basis. On behalf of the entire committee, I would like to extend special thanks to Dick for a job well done.

T.D. Lin, Chairman
ACI Committee 125, Lunar Concrete

EDITOR'S NOTE

As you read this ACI 125 Lunar Concrete Symposium volume, please keep in mind that this is the first of a series of papers that deal with lunar construction. The mission of this committee is to: **Develop and correlate knowledge and formulate recommendations for concrete construction on the Moon.** Six American spacecrafts, carrying two astronauts each, landed on the Moon's surface between 1969 and 1972. Much of this scientific data obtained during these missions has been used to form the basic logic incorporated in many of these papers.

The cover of this volume suggests an idealized flight path as a prerequisite for landing on the Moon and a return to Earth. Space Station Freedom, which will be constructed in the future, was omitted from this illustration because of scale. Our ACI logo, encompassed between the Earth and the Moon, depicts the international status of our ACI 125 Lunar Concrete as truly an international committee. The Moon is shown as full and the primary landing site was selected at random. As a brief primer for the Moon, a short discussion will follow to kindle your interest in this basic object within our Solar System.

The Moon is about one-fourth the size of the Earth and has a diameter of 2,160 miles (3,476 km). The average center to center distance from the Moon to Earth is 239,000 miles (384,500 km). If observed from space, the Moon orbits the Earth every 27 1/3 days, in a path that is less than 6% out-of-round. As the Moon orbits around the Earth, the Earth moves around the Sun. Both the Earth and the Moon are traveling together and therefore it will take the Moon about 29 1/2 days to reach a similar position in our sky. After inventing the telescope in 1610, Galileo discovered that the Moon had smooth and dark areas. He named the dark areas lunar seas, maria, even though there is no water in the depressions. A single sea is a mare, pronounced "MAH-ray". As the Moon's phases change from thin crescent (new Moon), to the waxing crescent, to first quarter, to waxing gibbous, to full, to waning gibbous, and to third quarter we on Earth see a changing Moonscape. As the Moon rotates around the Earth, it also rotates on its axis so that we see approximately the same half of the Moon surface. Also, half of the

Moon's surface is always lighted by the Sun. The half of the Moon that is lighted is a part of the surface that we see. The backside of the Moon is a part of the surface that we never see, except when photographed by orbiting missions. A new Moon or dark part of the crescent Moon can sometimes be seen as an "Earthshine" when light from the Sun's rays hits the Earth and is reflected back to the Moon. The Moon's phases directly influence the temperature of the lunar surface and vary from about -250 degrees F (-130 degrees C) to +250 degrees F (130 degrees C). Other useful constants may include: the eccentricity of the Moon's orbit is 0.054g, the Moon's gravity is about 1/6th of the Earth's, the Moon's surface area is $4.087 \times 10^{15} \text{ ft}^2$ ($3.797 \times 10^8 \text{ km}^2$), and the escape velocity at the surface is $7.79 \times 10^4 \text{ ft/s}$ ($2.375 \times 10^4 \text{ m/s}$).

As an introduction to the Lunar Concrete Committee's composition, please refer to the July 1990 issue of Concrete International and the article entitled **The Moon and "Back To The Future"**, within the section **Concrete: Yesterday, Today, & Tomorrow**. A reprint of this article follows this note along with a listing of the committee members. On behalf of ACI 125 Lunar Concrete, I hope you find this volume interesting and challenging.

Richard A. Kaden
ACI Committee 125, Lunar Concrete
Symposium Editor

Reprint from July 1990 Concrete International
Concrete: Yesterday, Today & Tomorrow

The Moon and 'Back To The Future'

by Richard A. Kaden

Just as Michael J. Fox, a young, successful actor who starred in three movies of this title, there appears to be an interesting and great future for the concrete industry in aerospace-related studies. ACI will play a very important role in meeting the challenges that lie ahead for marketing concrete and related support industries in space.

In March 1988, President Reagan announced that the lunar base program proposed by the National Aeronautics and Space Administration was included in the national space policy. ACI responded to the lunar base challenge by establishing a technical committee at the 1988 Fall Convention in Houston, Texas. The mission of ACI Committee 125, Lunar Concrete, is "to develop and correlate knowledge and formulate recommendations for concrete construction in space." Their primary goals are to:

- develop guidelines for new technology suitable for concrete construction in space
- collect information and identify areas of technical development and expertise
- stimulate interest in lunar concrete and assist colleges and universities to offer courses related to concrete construction in space
- provide assistance to those pursuing the goal of building manned lunar bases that will eventually serve as springboards to Mars

Dr. T. D. Lin, principal research engineer for the Construction Technology Laboratories was the founder of Committee 125 and is its first chairperson. He has organized a group of interested researchers,

scientists, and engineers into five subcommittees with special interests in lunar cement, concrete, construction, engineering, and education. Membership in the international committee has grown to over 40 experts in their own specialties. The Steering Committee is comprised of the subcommittee chairpersons and others. The Committee 125 secretary is Michael Gillen, and I am the committee's editor.

Each of the five subcommittees is chaired by specialists having an interest in the new technology:

Lunar cement — J. Francis Young chairs this group and is a professor of civil engineering, materials science, and engineering at the University of Illinois at Urbana-Champaign. This subcommittee will examine the possible strategies of developing a cementitious binder from lunar materials. The Lunar Cement group will review known terrestrial hydraulic cements and other inorganic binders and evaluate their potential applicability in light of the composition of lunar rocks and regolith, and the anticipated requirements for cement-based construction on the moon.

Lunar concrete — David O. Swint, professor and head of the U.S. Air Force Academy Department of Civil Engineering, chairs this multi-discipline group. Their task is to study and report research that is pertinent to aggregates, water, materials handling, and manufacturing processes necessary for lunar concrete. The mechanical properties, shrinkage, creep, durability, and air permeability are but a few of the laboratory study topics that will be monitored.

Lunar engineering — This subcommittee is chaired by Charles Lindbergh, professor and head of the Department of Civil Engineering at the Citadel, a military college in Charleston, South Carolina. Their primary goals are to establish a national lunar concrete construction technology baseline at the national grassroots level and to exercise it to produce the technical design and construction methodologies and data adequate to support the definition and implementation of a national program for lunar concrete base construction.

Lunar construction — Stewart W. Johnson, principal engineer, Advanced Basing Systems, for the BDM Corporation, heads this subcommittee. Their areas of study will include (1) automated equipment, power supply, mechanical friction, and remote sensing; (2) prestressing procedures and anchorage systems; (3) transportation of materials and structural elements; (4) construction methods, connection of elements, and planning; (5) sealants, maintenance, logistics, and structural safety; and (6) scheduling, energy requirements, labor requirements, costs estimates, and quality control.

Lunar education — Philip J. Richter, chief structural engineer, Advanced Technical Division, Fluor Daniel, Inc., and Menashi D. Cohen, associate professor, School of Engineering at Purdue University, co-chair this important subcommittee. The education group's aims and missions are to assist in assuring an interchange of information between all subcommittees and provide liaison with professional organizations and agencies. They will promote activities to provide information and gain public interest and support, including new

entries into the field, through seminars, symposia, workshops, and articles of interest for news releases and media coverage. The co-chairpersons will stimulate and coordinate participation in education and research and development activities with academia and industry. In addition to establishing a data base on pertinent subject matter, these educators will coordinate production of reports and publications on work by the entire Lunar Concrete Committee.

Technical symposium

Committee 125 and the Aerospace Division Committee on Space Engineering and Construction, ASCE, are cosponsoring the first Lunar Concrete Technical Symposium during ACI's Annual Convention, March 17-22, 1991. The call for papers is completed for original articles related to lunar and space applications of concrete and related construction materials and potential manufacturing methods.

There will be at least two sessions: one related to lunar cement and concrete; the second concerning engineering studies for lunar basing and construction of lunar and extraterrestrial base stations and specialized structures for optical and radio astronomy. The symposium will introduce concepts that will spawn new and innovative procedures for working in the harsh environments associated with space and planetary construction. Mark your calendar for a glimpse into the future.

Committee 125 appears to be a logical choice for establishing an international organization to focus on lunar concrete. It will be worthwhile to invite participation of important research figures from abroad to maintain a two-way flow of information on developments in lunar concrete technology.

ACI Committee 125
LUNAR CONCRETE

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* ACI Committee 125 Steering Committee which reviewed the papers in this volume.

** ACI Committee 125 members who contributed papers to this volume.

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SP 125-1

What Every Engineer Should Know About Gravity and Relativity

by G.D. Nasser

Synopsis: The age of space exploration is already here and it appears likely that in the next twenty years there will be permanent bases on the moon. Therefore, it is incumbent upon engineers designing lunar structures to become knowledgeable about the peculiar effects of gravity and relativity under extraterrestrial conditions.

The purpose of this paper is to present a review of Newtonian physics in light of Einstein's special and general theory of relativity. In particular, Newton's classic laws of motion and gravitation are compared with modern concepts of space-time, time dilation, length contraction, equivalency principle and other interesting aspects of relativity.

Keywords: Engineering; gravity; lunar bases; lunar structures; relativity; reviews.

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"I do not know what I may appear to the world; but to myself I seem to have been only like a boy, playing on the seashore, and diverting myself, in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

[Newton]

"I began to think of gravity extending to the orb of the moon and I deduced that the forces which keep the Planets in their orbs must be reciprocally as the squares of their distances from the centres about which they revolve: and thereby compared the force requisite to keep the Moon in her orb with the force of gravity at the surface of the Earth, and found them answer pretty nearly.

[Newton]

"Absolute, true and mathematical time, of itself, and from its own nature, flows equally without relation to anything external.

[Newton]

"A theory should be made as simple as possible, but not so simple that it does not conform to reality."

[Einstein]

"The effects of gravity and acceleration are equivalent."

[Einstein]

"A person in free fall is weightless."

[Einstein]

"Matter causes space-time to curve and space-time tells matter how to move."

[Einstein]

George D. Nasser, ACI Fellow, has been Editor-in-Chief of the PCI Journal (Precast/Prestressed Concrete Institute, Chicago, Illinois) for the past 20 years. Earlier, he worked as a structural engineer for several consulting engineering firms before joining the ACI Journal as a technical editor. He holds BSCE, MS, and doctoral degrees from the University of Detroit and the University of Michigan. He is the author of numerous technical papers that have been published in various engineering journals in the United States and overseas. Currently, he is a member of ACI Committee 125, Lunar Concrete.

INTRODUCTION

During the last 20 years, we have all been fascinated viewing the dramatic transmissions of astronauts floating in space, in a weightless condition, and watching the first men bouncing along on the moon's surface (at one-sixth their weight on earth). The force of gravity, which is related to weight, is indeed a mysterious phenomenon, the explanation of which has challenged some of history's keenest minds. By far, the two most important contributions on the subject were Newton's Principia (published in 1686) and Einstein's 1915 paper on General Relativity (see Fig. 1). However, prior to digging deep into these topics it is necessary to make some preliminary remarks and then review briefly the major historical events that led to Newton's and Einstein's ideas.

At the outset, one may legitimately ask why the subject of gravitation and relativity are relevant to this audience which is primarily concerned with the engineering aspects of lunar concrete. After all, the chances that we, in our lifetime or even in the foreseeable future, will be traveling at speeds near the velocity of light are remote. Such fascinating topics as time dilation, length contraction, mass increase, time travel and other relativistic effects occur only at these fantastic speeds.

And yet, there are some compelling reasons why a person should gain at least a rudimentary understanding of the subject.

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- * Experimental evidence has shown conclusively that the theory of relativity conforms to reality more closely than any other existing theory.
- * Today, every major university throughout the world offers one or more courses on relativity. To convince us of its popularity, all we need to do is visit any big library or modern bookstore to see the large number of books devoted to Einstein and his theory of relativity. As educated engineers and leaders in the age of space exploration we need to acquaint ourselves with the subject.
- * The theory of relativity has a direct bearing on cosmology (the science dealing with the origin and ultimate fate of the universe)... one of the fastest emerging disciplines. One major objective of the recently launched space telescope (which unfortunately was improperly designed) was to trace back the beginnings of the "big bang" -- the fireball that created our universe.
- * Einstein was one of the most original thinkers of all time who examined very fundamental concepts in our universe. As well-informed engineers, we should learn and be curious about such ideas.
- * The theory of relativity teaches us not to accept all evidence at face value. What may seem apparently true may in fact be an illusion. Throughout our lives, we face situations where our experiences may not conform to reality. Our built-in logic and intuition may, in fact, be a hindrance.

The purpose of this paper is to review the historical events regarding gravitation and the motion of bodies up to the present time. Newton's laws of motion are examined and compared to the results obtained using Einstein's special and general theory of relativity.

It should be emphasized that such a vast and complicated subject such as relativity cannot be covered in a single paper let alone

a series of articles. Therefore, only the highlights will be presented here. An extensive bibliography is included, at the end of the paper, for readers wishing to pursue the subject in greater depth.

HIGHLIGHTS

Let's start at the beginning. In ancient times (and in particular the Hellenistic world), the physical views of the Greek philosopher Aristotle (fourth century B.C.) were generally held. To summarize:

1. A force is needed to keep an object in motion. For example, in Fig. 2, the donkey has to maintain a continuous "pull" on the wagon to keep it moving at a constant speed. If the donkey stops, the wagon will also come to a standstill. Analogously, in a moving car we need to keep pressing the gas pedal to maintain a given vehicle speed. As soon as we release the gas pedal, the car will come to a standstill. It is only in hindsight that we know that a force of friction between the tires and the roadway (opposite to the direction of motion) acts to slow down the car.
2. There is a tendency for all moving objects, after some time period, to reach a state of rest. For example, a rock released from the top of a hill, will, after rolling a certain distance, come to a gradual stop.
3. Each of the four designated elements (earth, water, air, fire) had a natural resting place with the earth at the lowest level and fire at the highest level.
4. The earth was assumed to be at the center of the universe and to be motionless.
5. The planets were assumed to move in circular motion around the earth (see Fig. 3). For some of the planets, clever circular epicycles were superimposed on the large



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circles to account for their observed retrogressive motion.

6. Objects within the earth's sphere followed a different set of laws than the heavenly bodies (which followed the divine laws).

Based on the above concepts, all the known astronomical data of the ancient world were later summarized in the famous Almagest which served the ancient world surprisingly well for several centuries. The information was used widely by navigators in their travels and astrologers to cast horoscopes and to predict future events for kings and rival princes.

The state of the art remained almost unchanged until the 15th Century until Copernicus (1473-1543). His major contribution was to change the universe model to a sun-centered system rather than an earth-centered system. However, planetary circular motion remained the same as before.

Johanes Kepler's (1571-1630) major contributions were in formulating his three famous laws of planetary motion based on observed astronomical data. He accepted Copernicus' assumption of a sun-centered system but gave the planets elliptical orbits rather than circular paths.

Galileo Galilei (1564-1630) provided the next major breakthrough.

1. His use of a spyglass to observe the surface of the moon.
2. His experiments with balls rolling up and down inclined planes (see Fig. 4) which led to his law of inertia. (Newton later formalized this law into his first law of motion.)
3. His experiments showing that falling bodies with different densities (see Fig. 5) fell with the same acceleration. This experiment was vividly re-demonstrated by the first astronauts on the moon, see Fig. 6.

Even after Galileo was forced to recant his revolutionary ideas by the Catholic Church, he maintained that the earth moved.

NEWTON'S THEORY OF GRAVITATION

Isaac Newton's (1642-1727) greatest insight was to realize that the same laws of nature on earth also applied to the moon, planets and stars. He therefore, saw a connection between the motion of a freely falling object on earth and the "falling away" of the moon (see Fig. 7). Using a simple calculation $[16/(60 \times 60)]$, he found that the moon is "falling" 0.05 in. per second.

Newton's law of gravitation can be stated as:

$$F = \frac{Gm_1m_2}{r^2} \quad (1)$$

where m_1 and m_2 are point masses, r is the distance between them, G is the universal constant and F is the force of attraction.

In the above equation, it was assumed that the force of attraction occurred at a distance and also instantaneously. A further assumption was that the force of gravity acted at the center of the mass. As structural engineers, this is an assumption we use frequently with concentrated dead loads.

Newton himself was bothered by the aspect of "instantaneous action at a distance" but felt, with the knowledge he had, he could not answer the problem adequately.

Today, Newton's gravitation equation is regarded as historically important and a means of calculating the effect of gravity. Einstein's equations from general relativity (although mathematically much more complex) are regarded as far more precise and direct especially in fields of high gravitation. Engineers in the space program (with the availability of high speed computers) use more sophisticated methods for calculating the effects of gravitation than Newton's method.

Newton's laws of motion follow:

First Law: Every body continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.

Second Law: The change of motion is proportional to the force impressed: and is made in the direction of the straight

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line in which the force is impressed.

What Newton meant by "motion" involved not only a body's velocity, but also its mass. It is the quantity we call momentum, the product of mass (m) and velocity (v). Stated as an equation, the second law says that force is equal to the rate of change of momentum of an object.

$$F = \frac{d}{dt}(mv) \quad (2)$$

If the mass (m) is constant, then the equation reduces to the familiar expression, $F = ma$.

Third Law: To every reaction, there is an equal and opposite reaction.

The first law is a more precise restatement of Galileo's law of inertia. It is not in conflict with the theory of relativity and we see the law vividly demonstrated when applying thrust to rockets out in space or in touching objects within the cabins of spacecraft.

The second law ($F = ma$) forms the basis of classical dynamics and the Uniform Building Code formula for calculating seismic effects. For most practical conditions (as long as the velocity of an object does not approach the speed of light), it is a very precise formula. However, any physicist involved in nuclear physics with high speed subatomic particles would use Einstein's equations of relativity.

Newton's third law forms the basis of statics and our frequent use of free body diagrams. It is not in conflict with relativity or any other modern theories.

In developing his theories, Newton made two more assumptions which have some bearing on cosmology and relativity.

1. His equations were deterministic (one answer) rather than probabilistic (possibility of several answers) and presumed that the universe was unchanged throughout its history. This assumption had philosophical and religious implications.
2. Time and space were considered absolute. Einstein challenged this assumption and showed that time and space can not only be squeezed and expanded but are intrinsically linked together.

EINSTEIN'S THEORY OF RELATIVITY

Albert Einstein's (1879-1955) theory of relativity stands clearly as one of the greatest achievements of the human intellect, on a par with Newton's Principia.

Two centuries before, Newton considered time and space to be separated from each other and each to be uniform in character. He assumed that it is impossible to tell the difference in time from one point in time and any other. Thus, the universe looks the same if viewed either backward or forward in time, just as the recorded ticking of a clock would sound the same played either backward or forward.

Einstein discarded the notion of absolute space and time and showed that space and time were linked and together they could be squeezed, expanded or curved. In his special theory of relativity he assumed that the speed of light (186,000 miles per second) was an absolute limit that any object could travel. Fig. 8 shows velocity vs. time relationship for a constant force using Newton's second law and relativistic effects. From the graph, it is apparent that Newton's mechanics deviate from Einstein's theory and are not valid at speeds approaching the speed of light.

If the speed of light is constant, as Einstein maintains, then everyone should measure it to be the same - regardless of their motion. And since speed is just the distance an object travels over a certain period of time, Einstein concluded that it must be the passage of time that is perceived differently.

When applied to some imaginary situations, the theory of relativity could cause some bizarre effects (Figs. 9 and 10).

Suppose an astronaut is riding a spaceship at nearly the speed of light, every activity on board would appear perfectly normal to him. But to a person on earth something quite different occurs. Due to the Doppler effect, the spaceship appears bluer as it approaches the earth and redder as it recedes from this planet. Not only that, but the faster it goes, the shorter and more massive it appears, and the more slowly its onboard clock seems to run. Then just as the ship attains the speed of light, its clock seems to stop altogether, the length of the ship is reduced to zero and its mass has grown to infinity.

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Einstein's theory of general relativity presented a new way of looking at gravitation. In Newton's theory of gravitation, every entity which has mass exerts a force on every other object (Newton's law of universal gravitational attraction). Then each object changes its motion according to the resultant of all the forces acting on it (Newton's second law of motion). If there are no forces on it, an object moves in a straight line with constant speed, because that is the shortest path through space (Newton's first law of motion).

In Einstein's theory, on the other hand, every entity which has mass distorts the fabric of space-time. All objects pursue the shortest distance through space-time. Since massive objects warp space-time, the shortest path through space-time is not always the shortest path through conventional uncurved space.

One can envision this by considering an analogy. Imagine space-time to be a large trampoline. Two children are playing marbles on the trampoline. The goal of their game is to shoot the marbles as straight as possible, which can be easily done on the flat elastic surface. Each marble takes the shortest path along the surface, a straight line. Suddenly, a large rock falls on top of the trampoline, distorting its surface considerably. If the children attempt to resume their game, they find that the marbles no longer travel in straight paths along the altered surface; they curve in the direction of the unwanted intruder! By analogy, we see why massive objects distort space-time and cause other objects to move in curved trajectories.

Einstein's theory has been found experimentally to be more accurate than Newton's theory. However, the qualitative picture of planetary motion that arises from Einstein's theory is essentially the same as that from Newton's scheme. One would expect that to be the case because of the remarkable predictive success of Newton.

Let's compare how Newton and Einstein would each explain the motion of the earth around the sun. In Newton's description, the sun is seen as a generator of gravitational force because it has mass. The earth, wanting to continue in straight-line motion, finds it cannot, because of the sun's pull. Therefore, its motion changes, and it is forced to travel in an ellipse.

In Einstein's scheme, the sun is viewed as a distorter of the space-time fabric of a region of the universe. That means the sun alters the metric of the region. The metric describes all of the geodesics, or shortest paths, in the area. In a flat space-time, the earth travels in a conventional straight line in space, which is the shortest distance. However, because the space-time around the sun is distorted, the shortest distance in space-time becomes an ellipse. That is the path the earth is forced to take. The sun, in having mass, changes the shortest

distances between all of the objects in the area. The concept of force, as a pull between two objects, plays no part in Einstein's gravitational theory.

Early in his career, Einstein realized that a person or object in free fall experienced no weight (Fig. 11).

Einstein discarded the notion of force acting at a distance. He noted that the same quantity, i.e., mass, is involved in both Newton's second law and in his law of gravitation. He observed that if these two laws actually were independent, they would define two different kinds of mass. Newton's second law ($F = ma$) would define an inertial mass, and the law of gravity ($F = Gm_1m_2/r^2$) would define a gravitational mass. In fact, a number of precise experiments were carried out to see whether there was any difference between the inertial and gravitational masses of an object.

No difference between the two masses could be measured, and it seemed a remarkable coincidence that they should be the same. Einstein questioned whether it is coincidental that the same quantity is involved in both these laws. He decided that acceleration (as involved in Newton's second law) and gravity must be related. He then proceeded to show that it is impossible, in fact, to tell the difference between a gravitational force and an "equivalent" acceleration -- a relationship that has become known as Einstein's equivalence postulate.

As a simple example of the equivalence of gravity and acceleration, consider the hypothetical situation of a person standing in a spaceship in outer space (see Fig. 12) far away from any star or planet. If the spaceship is moving at a constant velocity, the person would experience weightlessness, just as the astronauts did on their trips to the Moon. If the spaceship were resting on a planet, the person would experience a force of gravity, giving him weight. Einstein's postulate indicates that the same effect could be produced by simply accelerating the spaceship.

From this effect many other phenomena, such as the bending of light can be understood.

In essence, Einstein stated that the gravitational force could be reduced simply to a geometric local effect. Specifically, mass grips space-time, telling it how to curve and, in turn, space-time orders mass how to move as shown in Fig. 13.

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CONCLUSION

Newton's laws of motion are not irreparably invalidated by Einstein's relativity theory. Rather, the definitions of some of the quantities that are calculated in mechanics must be changed. For example, it is necessary to restate Newton's second law in its original form, making force proportional to the time rate of momentum, and specifically recognize that in calculating the momentum as the product of the mass and velocity, the mass is not independent of velocity.

The unusual effects predicted by Einstein's theory of relativity occur only at extremely high speeds, i.e., at relatively high percentages of the speed of light.

At normal speeds that we are accustomed to here on earth and even current space travel, Newton's laws of motion are still valid.

Einstein's theory of relativity is worth our attention because it probes into the very fundamental laws of nature and prepares us to question many aspects of the universe which we might otherwise have taken for granted.

APPENDIX - REFERENCES

The references are divided into three parts for the reader's convenience and interest. The authors are listed in alphabetical order and the subjects are arranged in various degrees of mathematical complexity.

- A. Design-Construction Aspects of Building Bases on the Moon
- B. Historical Review of Gravitation, Relativity and Cosmology
- C. Mathematical Books on Relativity
- D. Books on Relativity With Less Mathematics

A. Design-Construction Aspects of Building Bases on the Moon

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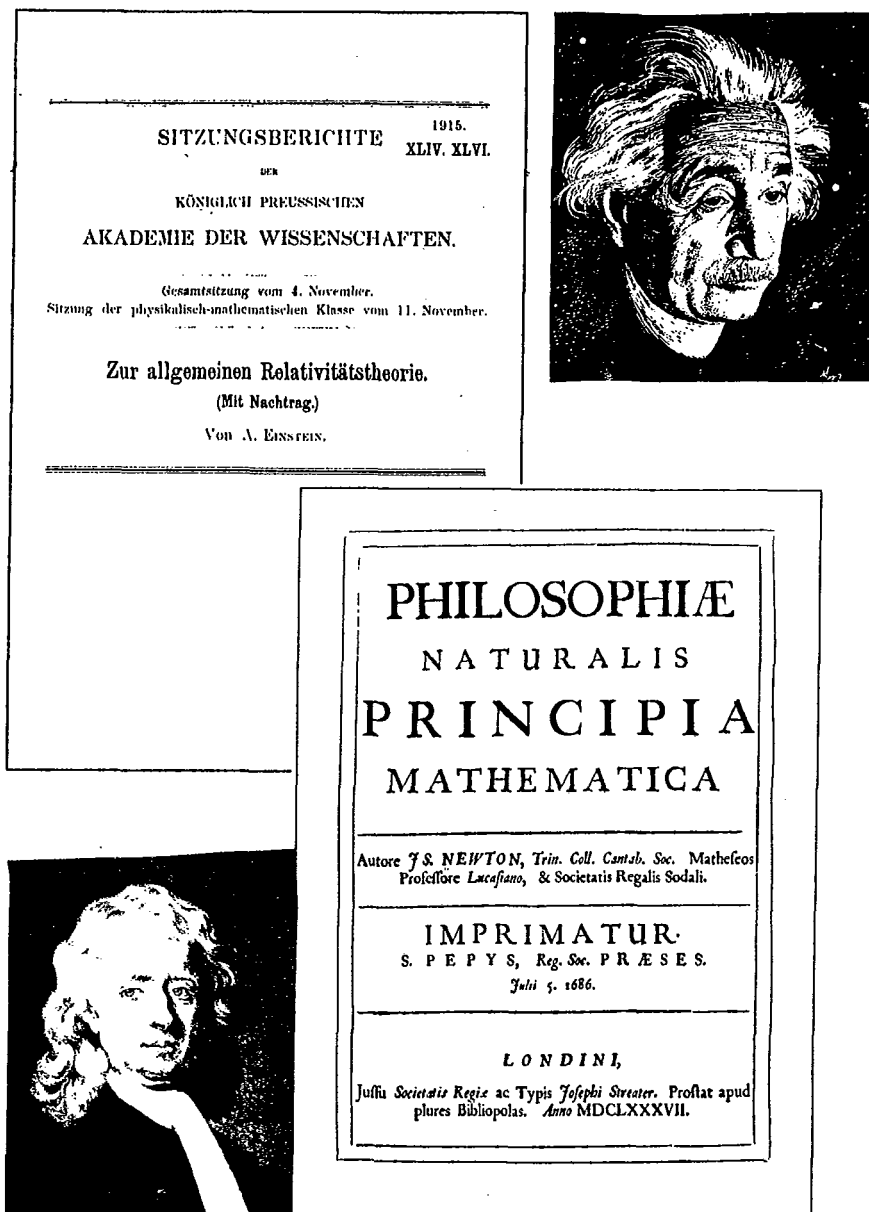


Fig. 1--Cover pages of Newton's 1686 Principia and Einstein's 1915 paper on general relativity. These works gave us the foundations for our two greatest theoretical advances in understanding gravity

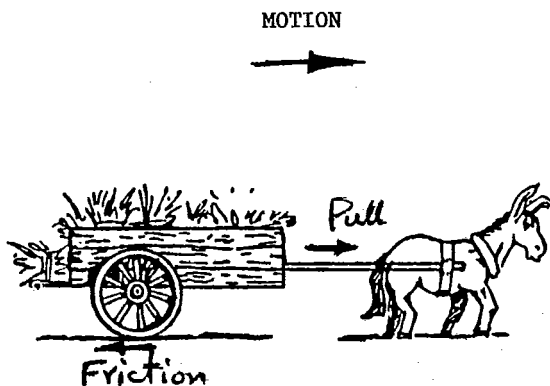


Fig. 2--To keep the wagon in motion, a continuous pull by the donkey is needed to overcome the force of friction between the wheels of the wagon and the roadway

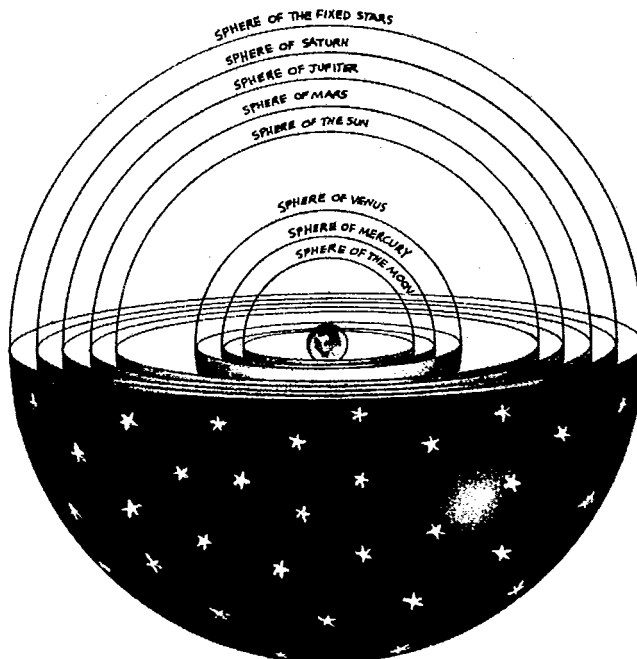


Fig. 3--The universe as viewed during the time of Ptolemy (first century A.D.). The earth was at the center of the universe and the moon, planets and stars revolved around the earth along perfect spheres

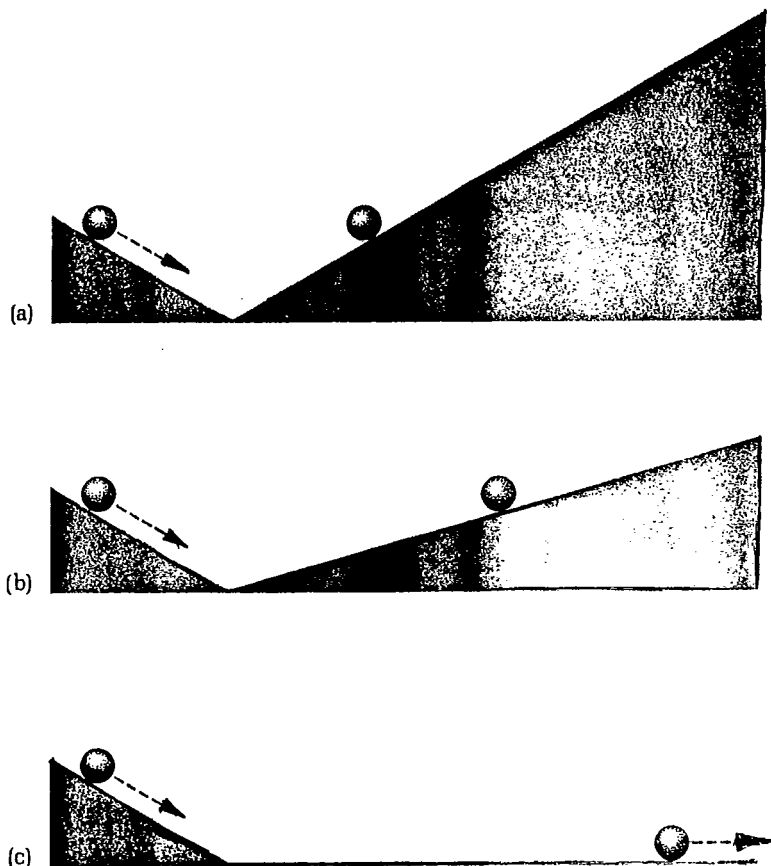


Fig. 4--Galileo arrived at the concept of the first law of motion through experiments such as the one illustrated here. A ball is rolling down an inclined plane, and it rolls up another plane to the same height it started with (a). As Galileo reduced the inclination of the second plane, the ball traveled farther on it (b). If the plane is horizontal (c), the ball would continue to travel forever, in the absence of friction or an intervening force

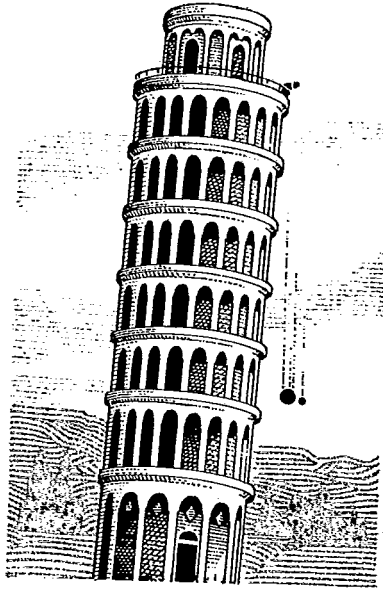
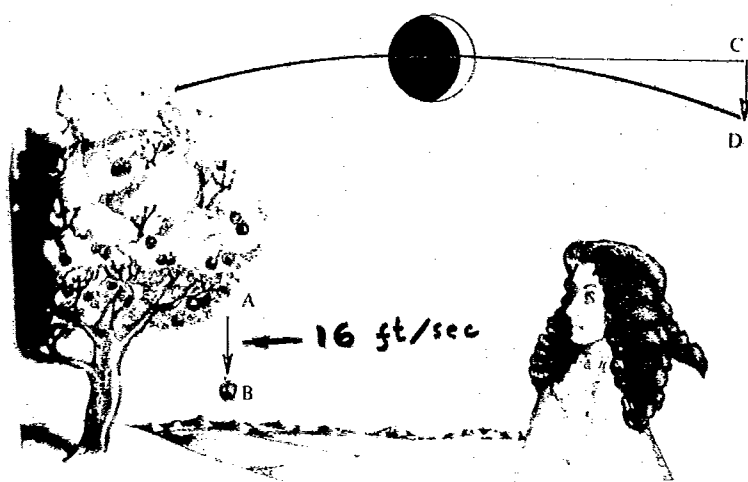


Fig. 5--Galileo dropped objects of various shapes and sizes from the top of the Leaning Tower of Pisa to demonstrate that all bodies fall with equal speed. The tower is 179 feet high and has a maximum deviation from the vertical of about 13 feet, corresponding to an inclination of just over 4°

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Fig. 6--Apollo astronaut David Scott dropping a falcon feather and hammer on the moon, showing that in a vacuum, both objects fell at the same rate



$$CD = [16 / (60 \times 60)^2] = 0.0044 \text{ ft}$$

Fig. 7--Young Newton's realization on universal gravitation went as follows: If the moon is 60 times as far from the center of the earth as is the apple (4,000 miles for the apple, 240,000 miles for the moon), and gravitation diminishes by the square of the distance, then the apple is subject to a gravitational force 60^2 , or 3,600, times that experienced by the moon. The moon, therefore, should "fall" along the curve of its orbit $1/3,600$ th as far each second as does the apple. So it does (time AB = time CD). The moon "falls" towards the earth 0.0044 ft per second (or about $1/20$ in. every second)

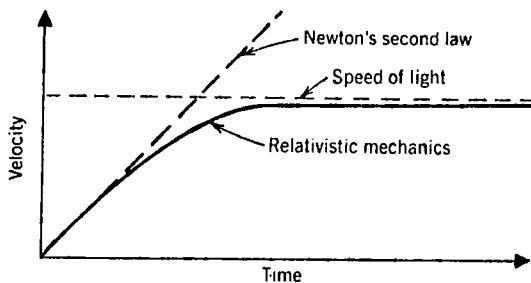


Fig. 8--Velocity versus time for constant force. In relativistic mechanics, the velocity cannot increase indefinitely, but rather is limited by the speed of light

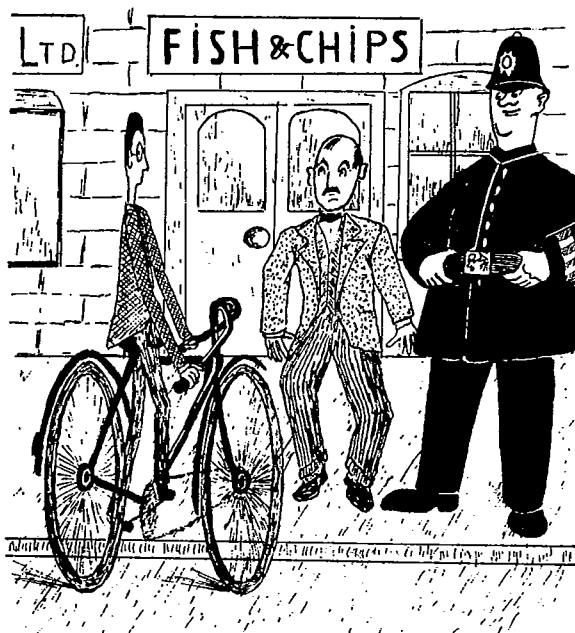


Fig. 9--To the standing policeman, the cyclist would appear unbelievably shortened .

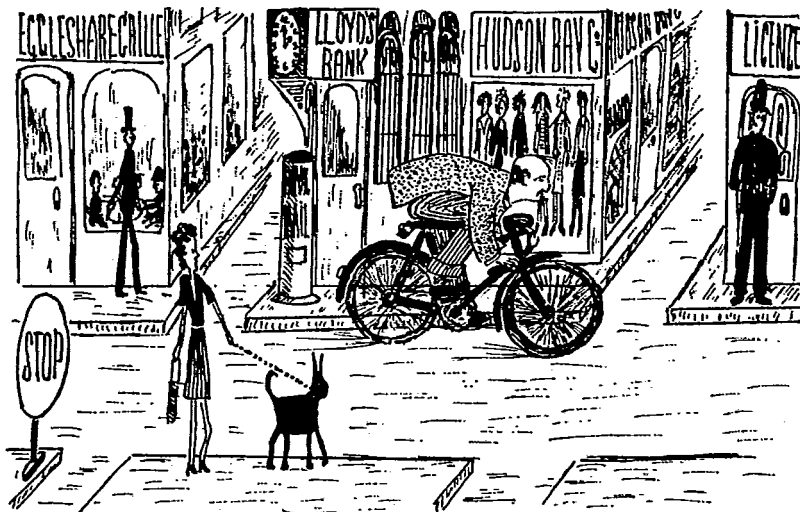


Fig. 10--To the moving cyclist the people and city blocks appear shorter

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Fig. 11--Skydivers in free fall are weightless

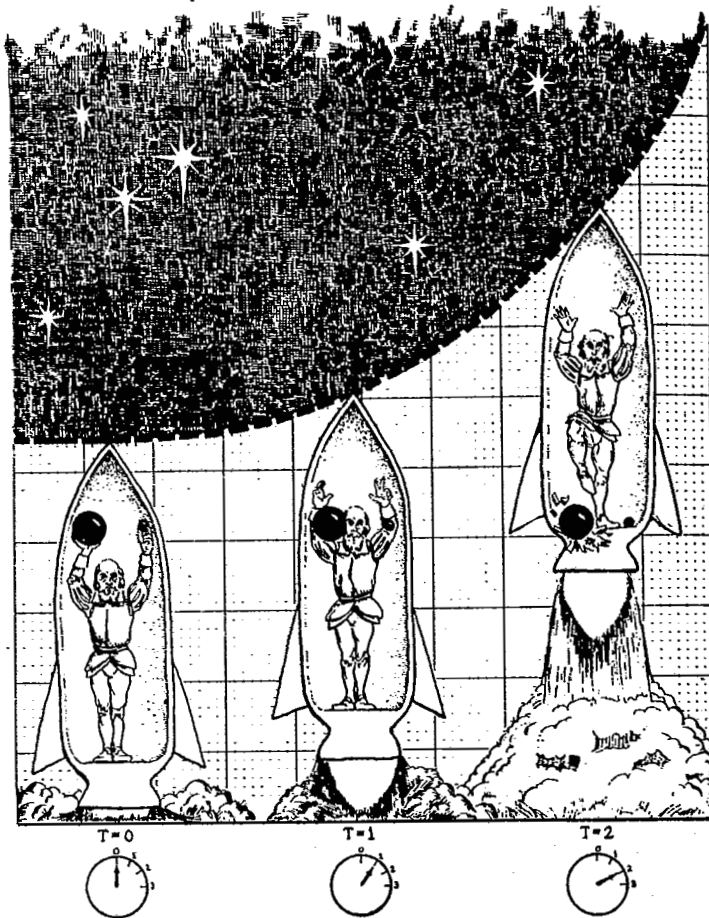


Fig. 12--Galileo performs his legendary experiment, not from the Leaning Tower of Pisa, but inside an accelerating spaceship. He releases two objects of different mass which seem to him to be falling exactly as they would on earth. Notice that the two balls are in fact not accelerating - they are in "free fall" and are not subject to any external forces. It is the floor of the accelerating spaceship that rushes up to meet them. This illustrates the equivalence of accelerated motion and gravity - the first postulate of general relativity theory

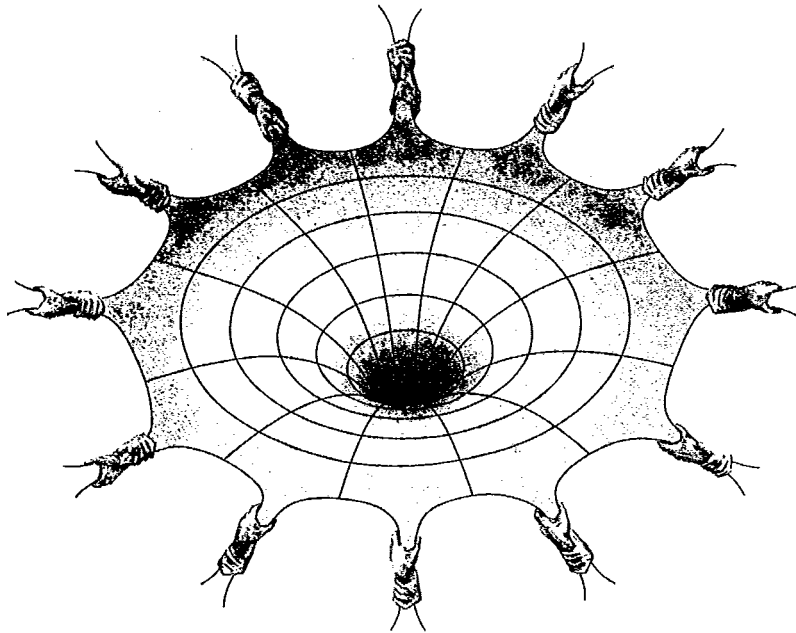


Fig. 13--Mass grips space-time, telling it how to curve, but also space-time itself grips space-time, transmitting curvature from near to far

SP 125-2

Cementitious Material Extraction from Lunar Resources

by S. Matsumoto, T. Yoshida, and K. Takagi

Synopsis: Lunar base concepts utilizing concrete as structural material have been proposed recently. These are based on the consideration that oxygen and raw materials used in manufacturing cement will be extracted from lunar resources and that the soils and rocks will be used as aggregates of concrete. The moon has an abundance of raw material used in manufacturing cement within its rocky soil, thus requiring rocks to be crushed. This paper discusses a unique rock breaking system using plentiful solar energy available on the moon. That is, sudden heating of a rock surface induces high thermal stress within the rock, which results in the rock breaking. Appropriate heat flow and radiating time are calculated using the physical property of basalt which has a similar chemical composition to lunar rock. Additionally, required system volume is estimated.

Keywords: Breaking; cements; extraction; lunar dust; lunar rock; solar energy; solar radiation; thermal gradient; thermal stresses.

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Tetsuji Yoshida is manager of the Space Project Office, Shimizu Corporation. He is the first in the world to introduce robots in the construction industry.

Kenji Takagi has worked at the Space Project Office of Shimizu Corporation for 4 years after serving at the Technology Division. He received a B.S. in Social Science from Tsukuba University in 1984.

INTRODUCTION

Concrete Lunar Base

Several lunar base related proposals include concept that utilizes concrete as a structural materials. The authors have also proposed concrete lunar base concept. An example image of the base, which consists of hexagonal column modules, is shown in Figure 1.

Advantages of Concrete

Using concrete on the moon has the following advantages.

- Suitable for radiation shielding
- Produced from lunar resources except hydrogen
- Simple production procedure
- Less energy for production

As mentioned above, concrete has a high potentiality for economic construction of lunar bases. Various kinds of research on lunar concrete are being conducted.

REQUIREMENTS

Mining and Excavation

Data acquired through unmanned and manned lunar explorations show that silica, aluminum, and calcium rich minerals suitable for manufacturing cement, are distributed at high land areas of the moon (Table 1). Since the soil of high land is rocky compared with the rest of the moon, a breaking process as a mining and excavation method will be required to

manufacture cement.

Concrete Production Flow

Concrete is produced in the series of plants shown in Figure 2. The regolith and rock will be utilized as aggregates while broken rocks will be used for manufacturing cementitious elements. The first phase will require efficient mining and excavation work.

Equipments

While equipment for excavation and mining on the moon would be expected to withstand the lunar environment, it would be desirable to include systems which effectively utilize the special environment.

ROCK BREAKING SYSTEM

Breaking Principle

It is well known that sudden heating of a rock surface induces a high temperature gradient and high thermal stress within the rock, resulting in the rock breaking. Since no atmosphere exists on the moon, solar rays reach the lunar surface without any dispersion, at a high radiation rate of 2.0 cal/cm²min. In this paper, rocks are broken through a system which utilizes solar rays by focusing and radiating them on rocks.

A schematic profile of the calculated thermal stress is shown in Figure 3. The figure shows a compressive force on the rock surface(A). The stress gradually changes to tensile force with increasing depth from the surface. Finally the stress reaches maximum tensile force at a certain depth(B). Since the tensile strength of a rock is around one tenth of the compressive strength, the rock will be broken at the point of maximum tensile thermal stress.

Breaking System

Figure 4 is a schematic drawing of the system. The converging mirrors arranged on the lunar surface send solar rays to radiating mirror A using a sun tracking system. A series of mirrors transfer the beam, converged by radiating mirror A, to the target point on the rock surface. The radiating lens B controls the quantity of the beam radiating onto the rock surface.

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Solar tracking--To converge solar rays effectively, a solar tracking unit will be attached as one of the important part of the system. The Shimizu solar daylighting system (see Figure 5), which has been developed to introduce sunlight into spaces previously regarded as impossible because of the structure of buildings on the earth, includes a capability for sunlight tracking.

Control of the system is achieved by a simple link mechanism that determines reflecting mirror movement. To control the mirror direction, the system has two tracking sensors; one for horizontal rotation and another for rotation about a horizontal axis.

Required heat flow calculation--For simplification, we assume a model, with the surface of rock having 2m of thickness receives a heat flow "q" (see Figure 6). The temperature distribution within the rock is given by solving the equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a} \cdot \frac{\partial T}{\partial t}$$

under the boundary conditions of

$$-\lambda \left(\frac{\partial T}{\partial x} \right) + q \Big|_{x=L} = 0, \quad \frac{\partial T}{\partial x} \Big|_{x=0} = 0, \quad T \Big|_{t=0} = 0$$

where,

T: temperature, t: time, a: temperature conductivity,
 λ : thermal conductivity.

In this case, the generated thermal stress is given by the equation as follows.

$$\begin{aligned} \sigma_x = \sigma_z = & -\frac{\alpha E T}{1-\nu} + \frac{1}{2c(1-\nu)} \cdot \int_0^c \alpha E T dx' \\ & + \frac{3x'}{2c^3(1-\nu)} \cdot \int_0^c \alpha E T x' dx \\ x' = x - \frac{L}{2}, \quad c = \frac{L}{2} \end{aligned}$$

E = Young's modulus of rock, ν = Poisson's ratio of rock
 α = Linear thermal expansion coefficient of rock

Assuming the physical properties of rocks on the lunar surface are similar to those of basalt on the earth, the physical properties listed in Table 2 would be used for calculation. Table 3 lists the heat flow 'q' radiated to the target spot on the rock surface, the time required to start

breaking the rock, and the depth of breakage.

Breaking capability--Based on the above analysis, this section discusses the possibility of a practical use of the breaking system. The heat flow 'q' which is sent by 1m^2 of a converging mirror to the targeted rock surface can be calculated under the assumptions that 10% of the beam attenuation occurs on a reflecting mirror and that 10 reflecting mirrors are necessary in a system. Therefore, initial heat flow from the solar rays is calculated as follows.

$$2\text{cal/cm}^2\text{min} \times 10,000\text{cm}^2 \times (1-0.1)^{10} = 7,000 \text{ cal/min}$$

According to Table 3, the most efficient case is the first one. Using this figure, the possible breaking capacity within an hour becomes

$$7,000\text{cal/min} / 10.675\text{cal/cm}^2\text{min} \times 20\text{cm} \times 60/40 = 0.02 \text{ m}^3$$

Converging mirror--Since the length of daytime on the moon is 336 hours, if we assume the volume of the lunar base area as $100 \times 200 \times 20 \text{ m}^3$, the surface area of the converging mirror required to cover the volume within one year is calculated as below.

$$100 \times 200 \times 20 / 0.02 / (336 \times 365/28/(\pi/2)) = 7,190 \text{ m}^2$$

The area corresponds to a mirror of approximately 85 m square.

In the case of smaller area breaking, mobile system will be desirable.

Breaking sequence--The radiated rock, as shown in Figure 7, divides the surface area into an appropriate mesh and is broken sequentially in 1-7-9-15-2-8-10-16 order. Since thermally breaking rocks may result in the development of cracks, making the rock brittle rather than broken, there is a need for a process to peel off the brittle rock portion.

Advantages and Disadvantages

This is an energy saving system because the only energy needed, other than solar rays, is for peeling off the brittle rock portion. Another advantage is that once the system is programmed, it can be operated by a remote control method.

The system has a disadvantage, however, of being incapable night work. Nevertheless, as determined above, the system is considered to have sufficient work capacity during only daytime operation. The mirror surface must also be protected from meteorites.

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CONCLUSION

In this paper, we have discussed an analysis on lunar rock breaking by thermal stress induced by converged solar rays. Though the use of solar rays is considered one practical method for a breaking system on the lunar surface, breaking experiments should be performed to confirm the capability of the proposed system under vacuum and solar ray environment.

After establishing the technology for this breaking system, applications will include various construction projects, such as ground leveling for launch/landing pads, road construction, and concrete breaking in the future.

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