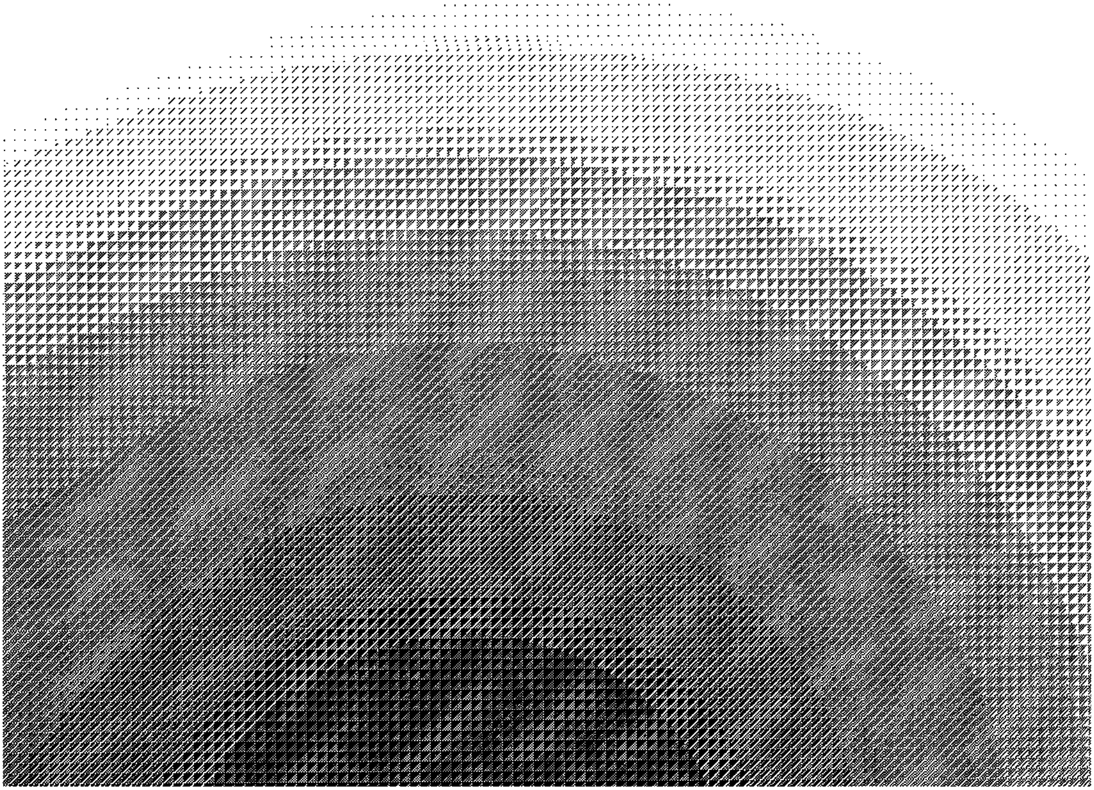
RETURN TO THE MOON



RETURN TO THE MOON

EXPLORATION, ENTERPRISE, AND ENERGY IN THE HUMAN SETTLEMENT OF SPACE

HARRISON H. SCHMITT

FOREWORD BY NEIL ARMSTRONG

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FOREWORD

By Neil A. Armstrong

I have in my library a book, published in 1896, entitled *The Sun*, by C. A. Young, PhD, LLD, Professor of Astronomy at Princeton. The learned professor easily discounts earlier theories that assumed that the Sun's energy resulted from the combustion of its gases. He wrote: "Even if the Sun were made of solid coal, burning in pure oxygen, it could last only about 6000 years. It would have been nearly one-third consumed since the beginning of the Christian era." That would result in a reduction in the size and energy output of the Sun, and a steady decrease in temperature of the Earth over the intervening centuries. The simple evidence of constancy in the growth of olive trees over two thousand years prohibited the possibility.

He examined two other hypotheses popular at the time: the chief proposed source of solar heat was (a) the impact of meteoritic material on the Sun's surface, or (b) the slow contraction of the Sun due to its own immense gravity. Without going into the detail of his elegant calculations, he ruled out the meteoritic theory and showed that the gravitational theory would yield a Sun that could only produce heat for about five million years. Something did not fit. Geologists had ample evidence that the Earth was far more than five million years old, and it seemed unlikely that the Earth would be older than the Sun.

Professor Young was short changed by time. In 1896, the same year in which Professor Young's book was published, Henri Becquerel, in France, discovered radioactivity. As we now know, radioactivity is a process wherein the atomic structure of certain elements naturally changes, giving off energy in the form of alpha, beta, or gamma rays.

In 1938, Otto Hahn and Fritz Strassmann transformed uranium into barium by neutron bombardment. The next year, Lise Meitner and Otto Frisch properly concluded that Hahn and Strassmann had split the uranium nucleus into a barium and a krypton nuclei giving off energy. Two foundations of science, the law of conservation of energy and the law of conservation of mass, were neither immutable nor mutually exclusive. Mass could be converted into energy! The implications were obvious to physicists around the world.

Hans Bethe received the 1967 Nobel Prize in Physics for his work on the nuclear reactions that are responsible for the energy-creating processes in stars. He proposed that hydrogen molecules, at extreme temperatures and pressures are "fused" into helium molecules. Some secrets of our Sun were beginning to be understood.

The Earth absorbs much of the solar energy bathing its surface then promptly radiates much of it away to the great empty space that surrounds us. The energy that remains is responsible for the Earth's temperature, the weather, and the existence of all plant and animal life. It is the engine that powers the Earth's water cycle from oceans to clouds to rainfall to creeks to rivers to oceans and lakes where evaporation reinitiates the entire process.

Few have ever believed that coal, oil and gas were unlimited resources. But known coal reserves are vast. 3-D seismography, deep-well drilling technology, and the ability to put wells in very deep water have managed to postpone the expected end of the oil era. Beginning in 1980, however, oil consumption outstripped new oil discovery and that deficit has been steadily increasing. Consequently, the number of years of known reserves is steadily decreasing. It is generally believed, therefore, that oil and gas will become increasingly expensive and the need for developing alternative sources of energy will be ever more obvious.

Such alternatives, fortunately, are numerous. Each has its advantages and disadvantages. Wind farms are growing more numerous in windy areas and are useful, but they are unlikely to become major contributors to the world's power needs.

Solar energy conversion is a possibility. Power from solar cells is available but is relatively highly priced. Panels in space could theoretically collect solar energy and beam it down to Earth but the practicality of the concept is unconfirmed. The use of solar power to produce hydrogen (and oxygen) from water is the subject of ongoing research.

The past quarter century has engendered interest in methane hydrates, a widely available fuel whose reserves are substantially larger than any of the fossil fuels, but have not, as yet, been commercially developed. Methane, however, like coal, contains a substantial amount of carbon and its combustion products are criticized for their greenhouse gas constituents.

Annual worldwide energy consumption is something more than 400 quadrillion BTUs and its production, conversion, and distribution is an enormous enterprise. No matter which of the many possible alternative concepts is selected for commercial implementation, it will undoubtedly require gargantuan investments

In *Return to the Moon*, Jack Schmitt presents another option for examination. This concept is dependent on three substantial and important developments: a commercial fusion reactor; an efficient mining operation on the Moon, and a reliable EarthMoon cargo transportation system. Each of these components is challenging and will require both substantial financial resources and the very best of intellectual talent. Each endeavor would be on the scale of a Manhattan Project or an Apollo Program.

Dr. Schmitt builds his persuasive case with a plethora of detail. He analyses the technical risks, the financial considerations, and the managerial and legal aspects. Readers familiar with this subject will find a goldmine of information to review and analyze. Those to whom the concept is revolutionary will find *Return to the Moon* thought provoking and exciting.

If you believe that Earth's increasing appetite for energy and the suspected future decrease in available energy will create an ever more severe problem for our Earth's population, you will find this proposal worthy of careful examination.

Neil Armstrong

ACKNOWLEDGMENTS

My wife, Teresa Fitzgibbon, provided the encouragement, editorial assistance, and many ideas without which the activities leading to this book would not have occurred. In addition to being the love of my life, Teresa makes that life happen.

From a technical and inspirational point of view, the nearly 20 year association with colleagues at the Fusion Technology Institute and various departments of the University of Wisconsin-Madison has been critical to the development of many of the concepts in *Return to the Moon*. Of particular note are interactions with Dean Gerald L. Kulcinski, Professor John F. Santarius, Dr Igor N. Sviatoslavsky, Professor Phillip E. Brown, Professor John (Jay) S. Gallagher, Professor Howard Thompson, Professor Richard B. Bilder, and the late Professor Eugene N. Cameron. Dennis Bruggink provided important graphical and computer assistance on many occasions. I also am particularly indebted to the hundreds of students who, since 1996, made teaching the course "Resources from Space" at Wisconsin such a stimulating and exciting experience.

I deeply appreciate Neil A. Armstrong's Foreword to *Return to the Moon*. Neil has made many unique contributions to the foundations of our knowledge about the Moon and its resources, including the gathering of critical samples of the lunar regolith discussed in Chapter 6. To have his insightful words accompanying a strategy to return there is both appropriate and gratifying.

An author needs all the factual and editorial help he can get. Such assistance, as well as encouragement, was thankfully received from Dean Gerald L. Kulcinski, Professor John F. Santarius, Dr Michael D. Griffin, Dr W. David Carrier, Professor Lawrence A. Taylor, Dr Gordon, and Jody Swann. Ted Lynn and Randall J. McDonald provided much needed early advice on publication matters. The patience, advice, and assistance of Clive Horwood, Dr John Mason, and Alex Whyte of Praxis–Springer, Tina Foulser of Bookens, and Paul Farrell of Copernicus, are much appreciated. Any errors or omissions, however, remain my sole responsibility.

Finally, I gratefully acknowledge the contributions and sacrifices of all the engineers, scientists, managers, technicians, support staff, contractors, astronauts, cosmonauts and their families who have participated in past space activities and fusion research. It will be on the foundations they have built, and for which the taxpayers largely have paid, that we will Return to the Moon and go beyond.

Harrison H. Schmitt
March 9, 2005

1

INTRODUCTION

ONE possible view of the future of humankind consists of a positive, expansive continuum – the "Star Trek" vision. That view assumes a continuation of hundreds of thousands of years of human migration into new habitats and the perpetuation of our search for new opportunities, personal fulfillment, and freedom. In modern times, this search has been particularly characteristic of "The English Speaking Peoples"[1] but not confined to this ethnic heritage, as witnessed by the achievements of migrants to the United States, Canada, and Australia from all over the world. These migrants came through a very special filter to survive and settle in new lands. For the most part, they came because of an intense desire to be free and to seek to better their social and economic conditions. The pull to these nations continues today. Mentally and physically, migrants could overcome the difficulties of leaving, of transit, and of the conditions of the wilderness. In special instances, they overcame slavery, servitude, and imprisonment. The future settlers of space will face no less a spectrum of challenges.

Return to the Moon encompasses a positive perspective for our future (Figure 1.1). It comes from nearly 40 years of my direct involvement with the space activities of the United States of America, including three days of lunar exploration as part of the 13-day Apollo 17 mission in December

FIGURE 1.1 Apollo 17 view of portions of the near and far sides of the Moon after leaving lunar orbit to return to Earth, December 16, 1972. (NASA Photograph AS17 152 23312)

1972. Additional insights come from 30 years of participation in and observation of national and international politics, including serving six years in the United States Senate. Finally, with my colleagues at the University of Wisconsin, there has been nearly 20 years of specific consideration of the role that lunar resources can play in the movement of human beings into space and in the betterment of the human condition on Earth.

In January 2004, President George W. Bush challenged NASA to once again "explore space and extend a human presence across our solar system." Those who believe in the future and in freedom embrace this vision of permanence in space for humankind. This new initiative places the President squarely in support of the movement of civilization into the solar system and "into the cosmos." If sustained by Congress and future Presidents, American leadership of this expansion of the ecological reach of our species will be accompanied by the transfer of human freedom, first to the Moon, then to Mars, and, ultimately, beyond.

President Bush's policy-driven initiative requires a sustained commitment of funding as well as tough, competent and disciplined management comparable to the Apollo Program of the 1960s and early 1970s. If the government of the United States wishes to lead the return of humans to deep space, its space agency of today is probably not yet the agency to undertake this new program. The National Aeronautics and Space Administration (NASA) lacks the critical mass of youthful energy and imagination required for work in deep space. NASA also has become too bureaucratic and too risk-adverse to efficiently address the President's challenge. To be assured of success, NASA would need to be totally restructured. Although some steps in this direction are occurring, the task faced by NASA remains formidable.

In restructuring NASA, it would be critical to use the lessons of what has worked and has not worked during 45 years of human activity in space. Of particular importance would be (1) that most of NASA be made up of engineers and technicians in their twenties and managers in their thirties, (2) the re-institution of internal design engineering activities in parallel with those of contractors, (3) the streamlining and delegation of management responsibility, and (4) the placement of senior managerial and technical leadership in the hands of experienced and competent men and women comparable to those who led Apollo. The existing NASA also would need to undergo a major rebuilding of its program management, risk management, and financial management structures. Restructuring is required to re-create the competence and discipline necessary to operate successfully in the much higher risk and more complex *deep* space environment relative to near-Earth orbit.

The United States has two basic options for both assuring results from, and the continuation of, a "sustained commitment" to deep space exploration and settlement. On the one hand, it could find a means to restructure and revitalize NASA and to provide it with a guarantee of continued funding sufficient to do the job – a tough order in the current national political environment, but one the President has directed NASA to undertake. Alternatively, the country's entrepreneurial sector could persuade national and international investors to make sustaining commitments based on the economic potential of lunar resources – which is not easy, but is at least predictable in terms of the conditions that investors require to be met relative to other uses of their capital. The option of rebuilding NASA is highly *un*predictable and its sustainability may depend on the appearance of a set of world circumstances comparable to those that faced the Congress and Presidents Eisenhower, Kennedy, and Johnson in the late 1950s and throughout the 1960s. Some, including the writer, would argue that those circumstances exist today, but no clear bipartisan consensus prevails on this point as it did in

1961. The American political environment is much more polarized than that during the Cold War. Now, opposition for opposition's sake is usually the rule.

Left unstated in the President's 2004 directions to NASA and requests to the Congress is an implicit challenge to the private sector of the United States to join in a reinvigorated migration into deep space. That sector of American life, particularly the entrepreneurial and investment risk-takers among us, should move forward in parallel with NASA's new efforts, protecting this unique economic foundation of American freedom. If private enterprise is to participate as more than useful and necessary contractors to NASA, then systematic business initiatives must be launched that will equal or exceed the technological and financial pace of publicly funded space efforts.

Although it fundamentally has an investor-driven economy, America has a tradition of parallel commercial and public technological endeavors, ranging from transportation to agriculture to communication to medicine. Such activities have often involved international partnerships and investors, and not all joint private and government efforts have been successful; however, enough have changed the course of history to warrant their consideration for space development. The creation of private trading routes, turnpikes, canals, and railroads helped to open the American frontier by building on the results of Lewis and Clark's Corps of Discovery, on Army expeditions that included the Corps of Topographical Engineers, and on waterway development by the Army Corps of Engineers. Since the 1880s, scientific research and technological innovations arising from the Land Grant College and University system have supported American farmers and associated agricultural businesses.

During the twentieth century, commercial aircraft and ground transportation industries grew in concert, respectively, with the research activities of the National Advisory Committee for Aeronautics and the construction of the Interstate Highway system. Satellite communications, the first venture into space-related business by private investors, was catalyzed by NASA's pioneering experiments and demonstrations in this field in the late 1950s and throughout the 1960s. The explosion in the quality of health care and in longevity since the 1930s has come in association with research breakthroughs by both the private sector and the National Institutes of Health. Many other beneficial and synergistic examples of parallelism can be cited, not the least of which was the introduction of commercial nuclear power.

Private and public endeavors operating together clearly have been far more productive than either would have been acting alone. In this vein, private space-related initiatives can benefit from the research and technology development funded by NASA and vice versa. The twentieth century, particularly since World War II and American stimulation of European and Asian post-war economic development, has seen research and technology development in other nations become positioned to participate in a privately led Return to the Moon initiative. That initiative also can supplement, support, and, if necessary, pick up the baton of space settlement if it is not carried forward by government.

The financial, environmental, and national security carrot for a Return to the Moon consists of access to low-cost lunar helium-3 fusion power. Helium-3 fusion represents an environmentally benign means of helping to meet an anticipated eight-fold or higher increase in energy demand by 2050. Not available in other than research quantities on Earth, this light isotope of ordinary helium reaches the Moon as a component of the solar wind, along with hydrogen, helium-4, carbon, and nitrogen. Embedded continuously in the lunar dust over almost 4 billion years, concentrations have reached levels that can legitimately be considered of economic interest. Two square kilometers of large portions of the lunar surface, to a depth of 3 meters, contains 100 kg (220 lb) of helium-3, i.e., more than enough to power a 1000-megawatt (one-gigawatt) fusion power plant for a year. In 2003, helium-3's energy equivalent value relative to $1.25 per million BTU steam coal equaled about $700 million a metric tonne and appears to be increasing to over twice that value by 2010. One metric tonne (2200 lb) of helium-3 fused with deuterium, a heavy isotope of hydrogen, has enough energy to supply a city of 10 million, or one-sixth of the population of the United Kingdom, with a year's worth of electricity, or over 10 gigawatts of power for that year.

By-products of lunar helium-3 production will add significantly to future economic returns as customers for these products develop in space. No such by-products are known that would warrant their return to Earth; however, locations in Earth orbit, on Mars, and elsewhere in deep space constitute potential markets. The earliest available by-products include hydrogen, water, and compounds of nitrogen and carbon. Oxygen can be produced from lunar water. Finally, metallic elements, such as iron, titanium, aluminum, and silicon, can be extracted from mineral and glass components in the lunar regolith (soil).

Over the last decade, historic progress has been made in the use of helium-3 fuels to produce controlled fusion reactions. This has occurred through the development of inertial electrostatic confinement (IEC) fusion technology at the University of Wisconsin-Madison. Progress there includes the generation of approximately one milliwatt of steady-state power in the form of protons and helium-4 nuclei produced by the fusion of helium-3 and deuterium (heavy hydrogen). Steady progress in IEC research, as well as basic physics, suggests that the helium-3 approach to fusion power has commercial viability (Chapter 5). Helium-3-based fusion, relative to other electrical plant options for the twenty-first century and beyond, can have inherently lower capital costs, higher energy conversion efficiency, a range of power from a hundred megawatts upward, and potentially no associated radioactivity or radioactive waste. Research and development costs to build the first helium-3 demonstration power plant are estimated to be about $5 billion.

As we reach toward the Moon and its resources, the development of fusion technologies will open new business opportunities in medical diagnostics and treatment, weapons detection, destruction of nuclear waste, and clean electrical power generation. Longer term, ancillary businesses will be possible because of low-cost access to space required to meet the demands of lunar resource acquisition. These additional business opportunities include providing services to the government for lunar and planetary exploration and science, national defense, and long-term on-call protection from asteroids and comets. Space and lunar tourism will also be enabled by the existence of such capabilities in the private sector.

A private, lunar resource-oriented enterprise will take a different technical path back to the Moon than the one designed by NASA (Chapters 4 and 7), and this dichotomy will be best for all concerned. More conceptional options will be explored, more engineering design approaches examined, and more opportunities for beneficial outcomes created. Indeed, successful commercial applications of fusion and space technologies to human needs and desires will underpin the private enterprise approach in contrast to the policy-driven foundation of the President's plan for NASA.

To provide competitive returns on investment in its lunar endeavors, the private sector will want heavier payload capability and lower cost in Earth–Moon launch systems than NASA appears to be planning. Private spacecraft will be specialized for the tasks of landing reliably and precisely at known resource-rich locations on the Moon rather than serving two or more masters such as the International Space Station *and* a Lunar Base. The private initiative will concentrate on lunar surface vehicles and facilities that provide reliable, low-cost resource recovery in addition to habitats for living. It also will require highly mobile and low-maintenance space suits that are less than half the weight and more than four times the mobility of Apollo suits, and have the glove dexterity of the human hand. All vehicles, facilities, and space suits will be designed for indefinite operational life, including embedded diagnostics, anticipatory component replacement, and ease of maintenance and refurbishment. Any required automated precursor missions to gather additional resource development information will use low-cost, data-specific approaches rather than attempt to meet broad, higher-cost scientific objectives. Research and development costs for launch and lunar operations equipment are estimated to be between $7 billion and $10 billion.

Management structures for a private initiative will follow proven corporate approaches and best business practices of comparable, high-technology enterprises (Chapter 11). These structures would be modified, as appropriate, by the lessons learned from Apollo (Chapter 9) for work in the complex and unforgiving environment of deep space. The Board of Directors and senior management will deal with programmatic issues involving planning, investors, conceptual approach, financial control, marketing and sales, governmental interfaces, public affairs, and the spin-off of ancillary businesses. Under this protective umbrella, responsibility to meet technical objectives will be delegated to several centers of excellence. Senior management will be drawn from any of the many private, federal, and defense sources where the most experienced and successful men and women can be found. A system of independent technical oversight will exist to assess these centers' readiness to proceed past programmatic milestones.

To minimize the amount of required inter-center coordination (and competition), centers will specialize, respectively, in Earth launch systems, spacecraft and flight operations, lunar resource extraction and processing, lunar surface support facilities, and fusion power systems. Centers of excellence will have internal design teams working in parallel with the implementing contractors, providing managers with two sources of information and opinion related to design and configuration control issues. Quality control and assurance will be managed as an internal responsibility of all employees and not just a centralized function of corporate headquarters. Critically, personnel management for the corporation will be charged with the need to maintain center organizations that are staffed mainly by workers in their twenties and managers in their thirties.

From early in its history, operational control of lunar activities will be placed on the lunar surface. Resource marketing and sales will be managed at corporate headquarters on Earth until those functions can reasonably be transferred to the its lunar surface operations. A private initiative will hire and support employees who wish to be settlers. From almost the first landing, the initiative's employees will be on the Moon to stay. All support functions, including medical treatment and rest and recuperation, will be provided on the Moon, not by a trip back to Earth. It will be a clear constraint on the design and operation of launch vehicles and spacecraft that there will be no significant stand-downs in the case of accidents. Rather, confidence in all hardware must be such that the next planned launch can proceed essentially on schedule.

International law relative to outer space (Chapter 12), specifically the Outer Space Treaty of 1967, permits properly licensed and regulated commercial endeavors. Under the Treaty, lunar resources can be extracted and owned, but national sovereignty cannot be asserted over the resource area. History clearly shows that a system of internationally sanctioned private property, consistent with the Treaty, would encourage lunar settlement and development far more than the establishment of a lunar "commons," as envisioned by the largely unratified 1979 Moon Agreement. Systems encompassing the recognition of private property have provided far more benefit to the world than those that attempt to manage common ownership.

The initial financial threshold for a private sector initiative is low: about $15 million. This investment would initiate the first fusion-based bridging business, that is, production of medical isotopes for point-of-use support of diagnostic procedures using positron emission tomography (PET). In contrast, the funding threshold for the United States government would be significantly higher: $800 million proposed for 2005 and building to an average annual addition of close to $1 billion. This latter estimate assumes both a repetitively willing Congress and a space agency capable of efficiently using this money as well as reprogrammed funds. The government, of course, would not benefit directly from the retained earnings of the fusion-based bridging businesses that are a natural consequence of the private sector approach.

The entrepreneurial private sector has an obligation to support a Return to the Moon to stay, as articulated by President Bush. We also have an obligation to follow our own path to get there in order to be additive to the overall goals of settling the Solar System and improving lives for those who remain on Earth.

Whenever and however a Return to the Moon occurs, one thing is certain: that return will be historically comparable to the movement of our species out of Africa about 150,000 years ago. Further, if led by an entity representing the democracies of the Earth, a Return to the Moon to stay will be politically comparable to the first permanent settlement of North America by European immigrants.

REFERENCE

1. Churchill, W. S., 1956–1958, *The History of the English Speaking Peoples*, Dodd, Mead & Co., 4 volumes.

2

APOLLO: THE LEGACY

2.1 INTRODUCTION

You are hereby directed . . . to accelerate the super booster program for which your agency recently was given technical and management responsibility.

President Dwight D. Eisenhower
Letter to T. Kieth Glennan,
NASA Administrator
January 14, 1960

I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to Earth.

President John F. Kennedy
Address to Congress
May 25, 1961

> 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 we are willing to accept, one we are unwilling to postpone, and one which we intend to win ...
>
> President John F. Kennedy
> Address at Rice University, Houston
> September 12, 1962

IN considering a Return to the Moon, it would be illogical as well as foolish not to examine the origins and legacy of the first human exploration of that small planet – Project Apollo (Figure 2.1). Much can be learned about the benefits to expect and the lessons that should be remembered. The lessons from Apollo will figure prominently in later chapters; here, it may be helpful to conduct a brief review of the Cold War origins of Apollo and its broad, beneficial legacies in the national, cultural and scientific histories of the United States and the world.

2.2 ORIGINS OF APOLLO

The initial catalyst for Americans venturing into deep space was the Soviet Union's October 1957 launch of Sputnik I, the first artificial satellite of the

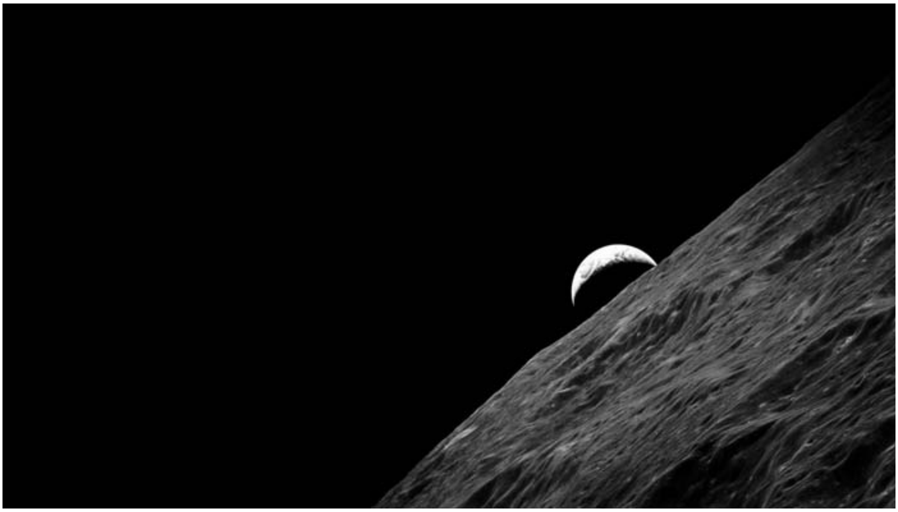

FIGURE 2.1 Earthrise from behind the Moon, one of the lasting symbols of Apollo. (NASA Photo AS17 152 23274)

Earth. It burst upon the American consciousness as one of the defining moments in the history of the United States. Although a temporary propaganda coup for the Soviets, the law of unintended consequences took over as a technological giant became focused on the obvious long-term importance of space. Thousands of young Americans began to think of space in the context of their personal futures and the future of the world and began to plan their education accordingly. The Eisenhower Administration and the Congress poured money into the public school system and into mathematics and science in particular. Other young aeronautical engineers in the National Advisory Committee for Aeronautics (NACA) began to study human space flight in general and flight to the Moon.

President Dwight D. Eisenhower's special message and legislation recommending the formation of the National Aeronautics and Space Administration (NASA) was sent to Capital Hill on April 2, 1958. Shepherded through Congress by Senator Majority Leader, Lyndon Baines Johnson, the resulting "Space Act" built NASA initially from the personnel, three field laboratories, and Washington Headquarters of the NACA. Eisenhower appointed electrical engineer T. Keith Glennan,[1] President of the Case Institute of Technology in Cleveland, to head the new agency. Hugh L. Dryden, last Director of the NACA, became Deputy Administrator. The President told the new Administrator, in Glennan's words, "he wanted a [space] program that would be sensibly paced and vigorously prosecuted."[2]

By the time NASA began operations on October 1, 1958, the nation had a strong foundation in aerospace technologies pertinent to the tasks ahead. For example, the NACA, from which NASA arose, had been established in 1915 "to supervise and direct the scientific study of the problems of [atmospheric] flight, with a view toward their practical solutions."[3] Gradually, the NACA moved from advisory coordination of the aeronautical research of various governmental agencies to a research agency status. It received funding in its own right with the Langley, Ames, and Lewis Research Centers conducting research in cooperation with industrial and federal engineers and scientists. In February 1958, General James H. Doolittle, hero of the early World War II bombing of Tokyo and chair of the main NACA advisory committee, had requested the first internal study on long-term research goals. Within its first year, NASA moved forward with these internal studies and one major set of contractor studies to define how human flights to the Moon and a landing on its surface might be accomplished.

On Glennan's initiative, the Army's Jet Propulsion Laboratory, managed by the California Institute of Technology in Pasadena, California was added to NASA near its beginnings as an agency.[4] Glennan, strongly supported by Eisenhower, also wanted Wernher von Braun's rocket development group in Huntsville, Alabama; however, the Army resisted this transfer for over a year. Finally, Eisenhower put his foot down and the new agency's initial field center configuration was completed in January 1960 with the final decision to transfer the Army Ballistic Missile Agency to NASA.[5] The Army rocket team, led by von Braun, became the nucleus of the new Marshall Space Flight Center to which also was transferred the Army's Missile Firing Laboratory at Cape Canaveral, Florida, later to become the Kennedy Space Center. The transfer of the Army Ballistic Missile Agency on January 1960 came with Eisenhower's personal directions "to accelerate the super booster [Saturn/Nova] program."[6]

Once the von Braun team had been established as a NASA unit, momentum increased steadily in the development of what became known as the Saturn family of heavy lift rockets and rocket engines, particularly the F-1 and J-2 engines.[7] The Army had started the development that led to these huge engines in December 1958 on the basis of a post-Sputnik recommendation by von Braun.[8] On several occasions, Eisenhower's personal intervention was significant in the continued development of huge launch systems.[9] The flight of Sputnik I, and growing belligerence on the part of the Soviet Union in relation to space and missiles, clearly left their mark on Eisenhower – as they had on many of my generation as well. In Washington, Eisenhower enlarged President Truman's President's Science Advisory Committee (PSAC).[10] To be its chair, he selected Dr James R. Killian, President of the Massachusetts Institute of Technology and thus the first presidential science adviser. Killian apparently was very influential in space-related matters during late 1957 through 1959.[11] Eisenhower's commitment to Saturn development, however, appears to be a prime manifestation of his personal concerns about space and the Soviet Union. On the other hand, to his subordinates, he occasionally professed a lack of enthusiasm for manned space flight in general[12] and flights to the Moon in particular.[13] Eisenhower's apparent antipathy toward man-in-space, particularly military man-in-space, only increased when the Soviets shot down Gary Powers' U-2 reconnaissance plane in 1960.[14]

In spite of such contradictory indications, it is difficult to believe, in view of his push for Saturn development, that Eisenhower had anything in the back of his mind other than human flights to the Moon.[15] As Glennan himself admitted in October 1960,[16] to what other reasonable use, in that day and age, could a 7.5-million-pound thrust rocket stage be put? The military had no defined requirements for thrust anywhere close to this level and no conceivable commercial satellites needed this capability. Only in 1960 – his last year as President, and in the preparation of the Fiscal Year 1962 budget he would hand to his successor – did Eisenhower attempt to hold federal spending for space and everything else into exact balance with projected revenues. This effort appears to have been based on principle and on regret that he had not done better in keeping his election promise to submit balanced budgets during previous budget cycles.[17] He undoubtedly realized that his successor and Congress would add significantly to his last budgetary requests for many parts of the government, including NASA. Indeed, this is exactly what happened.[18]

In retrospect, Eisenhower seemed split between his concern about the role of the United States as the protector of freedom in the world during the Cold War and his commitment to control the federal budget and the "acquisition of unwarranted influence … by the military–industrial complex.".[19] Still, on Eisenhower's watch, NASA came into existence, public education in math and science was enhanced, studies of manned flights to the Moon progressed, and a manned lunar booster project was aggressively pursued.

The most important managerial and political step taken early in the Kennedy Administration, unrecognized at the time, was the selection of the right person as NASA Administrator. This took place a little less than three months before White House consideration of a Moon landing initiative began. The leadership of NASA – one of the last positions to be filled by the newly elected President – had been the focus of a tug-of-war between Kennedy's science adviser, Jerome Wiesner, and Vice-President Lyndon Johnson.[20] In late January 1961, Senator Robert S. Kerr of Oklahoma suggested that James E. Webb, President Truman's Director of the Bureau of the Budget (now Office of Management and Budget) be considered. Weisner and Johnson both knew Webb well and were comfortable with the suggestion. Webb had many reservations about becoming Administrator, but with the assurance from Kennedy that Hugh Dryden would continue as Deputy Administrator, he took the job. Innovative management, and not reacting to Soviet actions, would be Webb's stated focus while Administrator.[21] The President even made a flat statement to Webb that he had no space policy and Webb would be responsible for creating one. Kennedy, however, may have influenced Webb by reportedly saying, "There are great issues of national and international policy involved in this space program. I want you because you have been involved in policy at the White House level [and] State Department level."[22] This could have sounded to Webb like an invitation to be bold.

In addition to Dryden (63), Webb (54) also retained Robert C. Seamans Jr (43), as the third member of the top management team.[23] In Dryden, Webb had a respected and experienced scientist and science administrator, and in Seamans he had inherited a top-notch engineer and engineering manager with strong contacts throughout the aerospace community and at MIT, where Seamans had taught. Webb, himself, had the Washington political and managerial insights necessary to operate in that competitive, cut-throat, political environment. He soon found that his primary adversary in the Washington environment, on the issue of space science versus manned space flight, would be one of his sponsors, Jerome Wiesner.[24] Weisner's efforts to control NASA would be backed by many of the scientists on the President's Science Advisory Committee that he led.

For a few months, Wiesner and the Bureau of the Budget, led by David Bell, were able to show progress in developing manned space flight capabilities. Events, however, began to take a life of their own. Kennedy personally approved going forward with "long duration Mercury flights" after budgetary discussions with Seamans and Bell on March 22, 1961, as they revised and augmented the FY1962 budget.[25] The "Mercury Mark II" project quickly evolved into the two-man, Gemini spacecraft. At that same March meeting, Kennedy also agreed to the restoration and enhancement of funds for Eisenhower's "super booster" as well as funds to "expedite supporting technology required for attainment of lunar goal." These actions signaled Kennedy's strong interest in manned lunar flights three weeks before Yuri Gagarin's flight into space and two months before committing NASA and the country to a lunar landing.

On April 12, 1961, the Soviet Union placed Gagarin in orbit around the Earth and returned him safely. Faced with the fact of the Gagarin flight and its obvious impact on Americans and the world, Kennedy held a Cabinet meeting two days later at which he asked what options the United States had in overcoming the Soviet lead in space. After the debacle in Cuba at the Bay of Pigs, an abortive rebel invasion that began on April 15, Kennedy's interest in a space initiative seemed to increase. Kennedy again brought up the possibility of a manned Moon landing in a memorandum to Johnson.[26] Kennedy asked: "Do we have a chance of beating the Soviets by putting a laboratory in space, or by a trip around the Moon, or by a rocket to land on the Moon, or by a rocket to go to the Moon and back with a man? Is there any other space program which promises dramatic results in which we could win?" At an April 21 press conference, Kennedy followed this with, "If we can get to the Moon before the Russians, then we should."

On April 24, in a meeting that included Webb and Wiesner, among others, Johnson received (that is, forced) unanimous agreement of his Space Council that a Moon landing should be recommended to the President. While Webb urgently gathered together the studies George M. Low and others had done to see if such an initiative were technically feasible, Johnson kept intense pressure on Webb to make an official, supportive statement to the President. On May 3, a still reluctant Webb told Johnson that (1) a manned Moon landing was one project the US could beat the Soviets in accomplishing, but only if (2) there was a sustained political commitment over ten years.[27] Through all of these deliberations, Weisner and others on the President's Science Advisory Committee gave only lukewarm support for human space flight.[28]

The situation changed even more rapidly on May 5 with Alan Shepard's successful and very public suborbital flight as America's first man in space. The next day Webb met with Secretary of Defense Robert S. McNamara, several of their respective senior staff, and Willis "Shap" Shapley[29] of the Bureau of the Budget to discuss what should be recommended to the President.[30] That evening, Seamans, Shapley, and a senior Department of Defense representative, John Rubel, prepared a draft report supporting a manned Moon landing. Later that same evening, Webb personally crafted this report into a formal presidential decision memorandum. The memorandum, signed also by McNamara, clearly affirmed that NASA, not the Air Force, would be the lead agency for the effort. In addition to outlining in considerable detail what would be required for the project to be successful, based on what was known at the time, Webb included identification of the need to support activities in space science and education. Important flexibility for developing space science activities in the future was created by this action.

Kennedy accepted Webb's decision memorandum, changing only one phrase. Then, on May 25, he announced to the nation that Americans were going to the Moon "before this decade is out."[31] The legacy of the success in meeting Kennedy's challenge resonates throughout the modern history of the Cold War, of human society, and of science.

2.3 COLD WAR LEGACY

Apollo clearly met the Cold War political goals set by Eisenhower through his quiet actions and by Kennedy through his political leadership, and met them far beyond either's original expectations. The intended intimidation of the leadership of the Soviet Union succeeded to the point where the success of the first test launch of a Saturn V booster convinced that adversary that the race to the Moon had been lost.[32] Apollo's example of what Americans could do when faced with an external challenge fed the Soviet's belief that President Ronald Reagan's 1983 Strategic Defense Initiative would be successful as well. That belief and the actual inability of a one-dimensional, military economy to compete in strategic defense was a major factor in hastening the collapse of the Soviet Union in the 1980s.

In parallel with Soviet discouragement, there came a rejuvenation of American pride. "If we can land on the Moon, why can't we —— (fill in the blank)" was the question often asked of astronauts making the speaking rounds. The answer is, of course, you can do "——," provided you can motivate young men and women to believe that achieving "———" would be the most important use of their lives. Those young men and women who were the heart and soul of Apollo, without exception in my experience, believed that putting an American on the Moon represented the highest achievement to which they could aspire. They gave youth, imagination, endurance, and in too many cases, their families to insure that the astronauts were safe as well as successful. Ten years of 16-hour days, eight-day weeks, required to meet John Kennedy's challenge would not have been possible without this willing and dedicated sacrifice.

2.4 HUMAN LEGACY

Apollo established a new evolutionary status for human beings in the solar system. The human species now has new, accessible, ecological niches away from the home planet (Figure 2.2), which expand our envelope for species survival. Our knowledge of the Moon, and now of Mars, shows that, eventually, humans can live on these bodies independently of support from Earth. The resources that are necessary to support human life exist on both. On Mars, large quantities of water-ice exist near the Martian surface[33] from which oxygen and hydrogen can be produced. The Martian carbon dioxide dominated atmosphere can provide methane-based fuels for many purposes.[34] On the Moon, solar wind derived hydrogen exists in the lunar soils at concentrations between 50 and 150 parts per million and even much higher in the polar regions.[35] The heating necessary to release the hydrogen causes it to react with soil minerals to produce water, estimated to be about one tonne of water per two tonnes of hydrogen.

FIGURE 2.2 Apollo 17 view of a nearly full Earth as photographed by the author from about 50,000 km on the way to the Moon. (NASA Photograph AS17 148 22726)

Local deposits of water-ice may also exist at high latitudes[36] although possibly not as much as some advocates may hope.[37] Helium and compounds of nitrogen and carbon are also released in significant quantities. As the fertility of the lunar soil is expected to be comparable to that of fresh Hawaiian volcanic ash, food production in properly shielded facilities appears to be feasible.

Importantly, for the economy of lunar settlers and for those left behind on Earth, about 1/2400 of lunar helium atoms are a light isotope, helium-3. Helium-3 has the potential to be a highly valuable export to Earth for use as a fuel for fusion electrical power production (Chapter 5). The major positive implications of this lunar resource on the personal and environmental well-being of human beings on Earth are discussed in Chapters 3 and 11.

Apollo also accelerated improvements in the human condition for billions of people on Earth. Its success gave hope to people world wide, as demonstrated by the reactions of those millions lining streets to see astronauts and cosmonauts on their world tours. It could be said, in light of subsequent history, that for many, such hope was misplaced. Indeed, the world and the United States did not build on the promise of Apollo. This neglect shows most egregiously in not using space exploration as a catalyst for education. Many in the world are worse off, or no better off, than they were when Armstrong first set foot on the Moon. This, however, is not a fault in the accomplishments of Apollo and its generation, but a fault in the socialistic human institutions that have stifled individuals who have attempted to realize its promise. On the other hand, the technological foundations expanded by, or because of, Apollo have revolutionized the world's use of communications, computers, medical diagnostics and care, transportation, weather and climate forecasting, energy conversion systems, new materials, systems engineering, project management, and many other applications of human ingenuity.

2.5 SCIENTIFIC LEGACY

A great beneficiary of Apollo has been and continues to be the science of the Earth, the planets, and the solar system. From the samples collected and placed in context by the astronauts, there came a first-order understanding of the origin and history of the Moon. Debates related to specific questions about lunar origin and history continue,[38] particularly as to whether the Moon was formed by a giant impact on the Earth or was captured by it at a later stage. Competing hypotheses can be tested, however, using the real information from samples. The foundation provided by Apollo exploration has allowed calibration of global interpretations of subsequent remote sensing from lunar orbit by the Galileo, Clementine and Lunar Prospector missions. The combination of Apollo and remote-sensing information has given us a general perspective of the accretionary and cratering history of the inner solar system that is unavailable anywhere else other than, possibly, on the distant planet Mercury, which is currently inaccessible to direct human exploration. The inner solar system's cratering history, in turn, has provided a guide to the early history of Earth, Venus, Mars, and Mercury, including new insights into the conditions under which life's precursors and life itself formed on Earth, and possibly on Mars.

Lunar science, as developed from Apollo data – combined with our ever-expanding knowledge about the Earth – became the basis for the new discipline of "comparative planetology," now one of the most active and multidisciplinary aspects of science. The extraordinary interest in recent robotic exploration of Mars shows that comparative planetology also has captured the public's attention. Combined with the delineation of the potential of lunar resources discussed above, this was not too shabby a result for a Cold War stimulated effort that initially did not consider science as a potential beneficiary.

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3

ENERGY: THE GLOBAL FUTURE

3.1 INTRODUCTION

THE economic, technical and political potential of returning to the Moon for helium-3 to fuel fusion reactors on Earth must be evaluated in the context of probable global demand for energy and reasonably competitive alternatives for meeting that demand. In this context, the immediate challenge to civilization's global energy future lies in meeting the needs and aspirations of the 10 to 12 billion earthlings that will be on this planet by 2050.[1] Current per capita use of energy is equivalent to about 12 barrels of oil per year for a global total equivalent of about 72 billion barrels of oil equivalent (BBOE) per year,[2] or about 410 quads (1 quad = 10^{15} BTU) per year.[3] It can be argued, conservatively, that at least an eight-fold increase in annual production will be required by the middle of this century (see Table 3.1). That includes a two-fold increase to account for the increase in the world population from 6.3 to 12 billion and a four-fold increase to meet the major aspirations of four-fifths of the world's peoples whose standards of living are far below those of developed countries. Even an eight-fold increase would not bring the rest of the world to the current average per capita energy use in the United States of about 62 barrels of oil per year equivalent. As seen in Table 3.1, that would take at least an 11-fold increase, not counting the demands of new technologies and climate change mitigation.

TABLE 3.1 Projected global growth in electricity demand by 2050[4]

Growth category	Per capita
Current demand	12 BBOE(1)
Population doubling	12
Added economic growth (US today)	62
New technology demand	?
Climate change mitigation	?
Total for 10 billion persons	860 BBOE
2050 Demand/current demand	11

(1) Billion barrels of oil equivalent

The choice of an "aspiration" or economic growth increase of a factor of 4 is somewhat arbitrary. It represents, however, a level that would not only relieve much of world poverty and many international tensions but would also provide a measure of indirect control of population growth if not population stabilization at 10 to 12 billion. The only historically proven means of a significant reduction in population growth lies in improved standards of living. Human experience shows that only increased energy consumption can provide such increases in living standards on a nation-by-nation basis. Of course, most nations that have both poverty and high fertility rates do not have political and economic systems that encourage increases in standards of living. That problem cannot be solved by new sources of energy supply but must be dealt with by example, education and persuasion.

A comparison of the per capita energy consumption of countries that have raised living standards (and reduced birth rates) significantly in recent decades suggests that an addition of a factor of only 2 to 4 to world energy supply by 2050 would have a major impact on population growth. For example, the annual per capita consumption of energy (in BBOE) in South Korea and Turkey increased from 7.6 and 4.0 in 1980 to 31 and 7.9 in 2002, respectively. The annual population increases in these two countries have decreased from 1.5 and 2.2% in 1980 to 0.6 and 1.5% in 2002, respectively.[5]

With respect to aspirations, China and India represent special cases in which a desire for economic and political dominance in the world, particularly on the part of China, also drives increasing electrical power consumption. Because of their huge populations and accelerated growth, these two countries will have inordinate influence on the future of total global demand. The contribution of the total standard of living "aspirations" to future global growth in per capita electricity demand can only be roughly estimated today. If it is as great, however, in the next 50 years as it has been for South Korea and other countries that have successfully entered the modern industrialized world, then growth of a factor of at least 4 must be added to projected demand by 2050.

An additional source for growth in electricity demand will come from the need to counter the adverse effects of climate change. With respect to such change, one conclusion is certain from historical, archeological and geological records: climate will change and sometimes change rapidly over a few decades. Independent of human influence, climate change has appeared as gradual warming over several centuries, as rapid cooling over a decade or so, or as rapid oscillations over a century or two.[6] Whether human activities will exacerbate these natural swings in climate is not known for certain,[7] although preliminary global climate models currently forecast continued warming.[8] We have no ability as yet to reliably predict which way the inevitable change will occur. What can be reliably predicted is that more electricity and more energy in general will be required to mitigate the adverse consequences of such changes, whether from warming or cooling.

Another problem that can be solved by new sources of energy is the reduction and eventual elimination of the dependence of the world's democracies on unstable sources of energy supply, sources over which there exists little or no market control of prices. In this context, however, it is assumed that financing of new capacity will come largely from the private sector. Financing any major increase in capacity through tax revenues would destroy the economic incentives necessary to drive democratic economies. On the other hand, development of new energy technologies, in contrast to their actual penetration of the energy markets, probably can be accomplished best by a cooperative effort between government and private enterprise. Such cooperation historically has been the case for much technological advancement. Of particular note would be government–private cooperative research and development in ground, sea, and air transportation, agriculture, medicine, and communications, as discussed in Chapter 1.

3.2 "IN THE BOX" ENERGY SOURCES

The energy sources that can be considered developed and "in the box" for consideration as sources for major increases in supply over the next half century are fossil fuels, nuclear fission, and, to a lesser degree, various forms of direct and stored solar energy. Unfortunately, a combination of political, geological, terrorism, and environmental factors combine to force a conclusion that these currently developed sources of energy cannot provide a major increase in supply by 2050, much less an increase by a factor of 8 or more.

3.2.1 Fossil fuels

Fossil fuels can be broadly defined as crude oil, natural gas, coal, tar sands, and special sources of methane (coal bed gas,[9] shale gas,[10] pressurized basin-centered systems,[11] and sea floor hydrates[12]). Well-developed technology and reserves related to crude oil, natural gas, coal and coal bed methane clearly constitute our current number one "ace in the hole" in meeting near-term future demand.[13] Following the 1950s lead of M. King Hubbert,[14] however, many observers[15] believe that total annual production of these four sources of fossil fuels will peak, due to natural geological limitations, between 2010 and 2030 at about 75 billion barrels of oil equivalent. Crude oil, currently being produced and used at a rate of 30 billion barrels per year, will peak first, natural gas next, and coal much later. As they have in the past, those production peaks can be pushed to later decades and higher levels by higher prices, new technology, decreased political restrictions on exploration, revised definitions of what is "oil," and substitution of alternatives. Some natural limit on economical fossil fuel availability, however, clearly exists, but geologists and engineers never cease to become more and more inventive. On the other hand, indefinitely increasing fossil fuel supply by several factors in the face of steady, routine increases in demand seems impractical.

Coal represents a somewhat special case within the fossil fuels category of energy sources because immense reserves of varying energy content and sulfur concentration exist throughout the world. In the United States, however, access to those reserves continues to be hampered by litigation of various kinds.[16] Globally, coal use is under fire because it contains more carbon relative to hydrogen than other fossil fuels, and thus releases more carbon dioxide per unit of energy. Coal also is a source of low levels of mercury emissions. Although of significant political concern, their impact on human health is not clear.[17] "Clean coal," coal to oil, and coal to gas technologies continue to be of interest in the United States and elsewhere and, along with various carbon sequestration techniques, have the potential to improve coal's environmental reputation as well as prolong its use as a long-term energy source.[18]

Even though water vapor constitutes by far the principal greenhouse gas in the Earth's atmosphere,[19] carbon dioxide, with its possible effects on global climate, has become a international political issue in recent years. The interaction of the extremely complex natural carbon cycle with increased carbon dioxide produced by human activities remains poorly defined; however, there is general reluctance to add any more of this gas to the atmosphere than is absolutely necessary. A similar greenhouse potential exists with releases of methane that is not captured during the extraction of fossil fuels in general or is released by natural and agricultural processes. Burning coal also creates ash and gaseous oxides of nitrogen and sulfur that contribute both to pollution and acidic rain and that have accompanying capture and disposal problems. The amounts of these waste products depend on where the coal comes from and the degree of regulation imposed on its use. Further, some coal ash has high concentrations of radioactive elements that can be of concern in some situations. For the foreseeable future, in spite of the above issues, coal will continue to be tapped as a primary source of fuel for generating electrical power because of its broad availability and its mature technology base and supply infrastructure.

Supplies of fossil fuels will always be very sensitive to price and the predictability of that price, not to mention the difficulties of finding and producing these materials from increasingly more complex, generally deeper, and more hostile geological environments. Additional and more costly resources may be identified and tapped by private companies at higher prices if these prices can be assumed to be stable at least until development costs are paid off. These frontier fossil fuel resources include deep-sea crude oil production; very thick, deep or less clean coal beds; tar sands; deep pressurized methane brines; and sea-floor methane.[20]

The problem for investors and governments in predicting short- or long-term price stability of fossil fuels, particularly for crude oil, lies in the obvious political and security instability of the Middle East and in the terrorist, political, and economic motivations of various Middle Eastern regimes. It is not even clear that the reported reserves (proven resources) from these countries, and from some major oil companies, are correct. They may be significantly inflated.[21] Also, several international companies have recently revised their published reserve estimates downward. Price is under the control of the same regimes with questionable reserves, dominated by Saudi Arabia. Artificial oil production limitations have been and could be used again in attempts to intimidate the world's democracies (oil embargo of the 1970s). Clearly, if democratic governments can be established in Afghanistan and Iraq and integrated into the world democratic community, the long-term stability of the region and of oil markets may be one of many positive results.

A major, relatively new factor in the future of fossil fuel markets and supply arises from the economic growth of China[22] and India and, to a lesser extent, from other developing economies.[23] China's entry as a buyer in world crude oil and coal markets, for example, already appears to be causing prices of these commodities to rise. If China continues to successfully raise its standards of living, and other developing countries do likewise, fossil fuel demand and prices will increase further, at some point finally opening the door for new energy technologies.

Pressures on supply and price also exist for natural gas. The desirability of low carbon natural gas, specifically methane, as a relatively low polluting fuel for electric power plants has rapidly increased its use. An increase in consumption of about 3% per year for the United States is a rate less than the rate of identification of new reserves and increases in production capacity.[24] No clear data exist, however, on how long this relationship can be maintained. In addition, if the United States and other countries succeed in developing hydrogen as a portable fuel for automobiles and other users, an accelerated demand for natural gas will arise, at least until non-fossil-fuel-based hydrogen production is economic. In this regard, the use of natural gas, or any fossil fuel, to produce hydrogen constitutes a method of energy storage, and its conversion to useful energy, such as use in fuel cells or internal combustion engines, is inherently more inefficient than direct burning. The net result of a near-term increase in the use of hydrogen will be an increase in the use of fossil fuels, absent a means of direct production from solar energy, waste heat, or off-peak use of electricity produced by fission or fusion power plants.

Fossil fuels also are under increasing regulatory pressures due to concerns about the health effects of hydrocarbon and sulfur dioxide pollution as well as the potential effects on climate from carbon dioxide and methane emissions. The Kyoto climate treaty,[25] in fact, is an attempt to roll back the use of fossil fuels in developed countries, particularly the United States. Many nations advocating the Kyoto mandates probably have their motivations more in gaining trade and other economic advantages over the United States than in preventing significant climate change. None the less, regulation or restriction of the use of fossil fuels increases the costs of energy derived from them, or from more expensive alternative sources, and thus increases the prices consumers must pay for fuel or electricity and for most manufactured and agricultural goods.

The scientific merits of concerns about both climate change and the health effects of hydrocarbon and nitrogen and sulfur oxide pollution will continue to be debated. The other agendas embedded in these debates lie beyond the scope of this book. Suffice it to say that the scientific arguments about health effects are discussions on the statistics of small numbers of people who are affected by numerous other health-related factors and are generally exposed to indoor rather than outdoor environments. If the health effects are real, then it is clear that we do not know what physiological mechanisms cause these problems. Scientific arguments about climate change rest on the validity of complicated and still incomplete computer models and on the inevitability of change, either warming or cooling or a combination of both, within a geological context. The political arguments about these issues reflect the ongoing debate between proponents of larger government and limits to economic growth on the one hand and proponents of market-driven solutions to most societal problems on the other. None the less, the politics of climate change will not be resolved soon, and pressures to add the costs of carbon sequestration to those of fossil-fuel-based power generation will continue to increase.[26]

Given all the natural and political pressures leading to a decrease in the rate of growth in the supply of fossil fuels, and an increase in their price to users, one must conclude that it would not be prudent to depend on this source of energy to meet the increasing demand for more than a few more decades. Further, fossil fuels really consist of "fossil chemicals" of great future value in the production of many other materials of great use to society (in agriculture, consumer products, etc.). As their future value as feedstocks increases, market limitations on their use as fuels may actually be favorable in the long run of human history.

3.2.2 Nuclear fission

The use of nuclear fission (the splitting of atoms of heavy and radioactive elements like uranium and thorium) to produce electrical power currently produces about 4.6 billion barrels of oil equivalent in electrical power annually, world wide. It constitutes our second "ace in the hole" relative to meeting major demand growth for energy. In the United States, nuclear power produces about 20% of all electricity and, in recent years, has grown in its share of the power market due to improved online performance and regulatory extensions of plant life. Availability (capacity factor) of the 103 fission plants in the United States averaged 91.3% in

2002.[27] France currently produces about 80% of its electrical power through nuclear plants, and has been increasing this percentage steadily, while Japan has leveled at about 28%. Worldwide, 17% of electricity comes from about 440 nuclear plants.

The technology of nuclear fission for commercial and defense energy supply has always been the safest relative to other major power sources. Over time, real operational risks have gone down significantly. Perceived risks, however, continue to be high due to negatively biased education and media reporting on the level of actual hazards that exist from fission plants. In fairness, the designs of nuclear plants built and exported by the former Soviet Union were seriously flawed, as the 1986 Chernobyl accident in Ukraine so sadly demonstrated. However, plants in use in the United States, Japan, France, and most other countries have an outstanding safety record. Even when problems have occurred, as in the case of Three Mile Island in 1979[28] and Brown's Ferry in 1975,[29] the containment and backup cooling designs worked to prevent any problems in health and safety even though serious issues of plant design and operational procedure were uncovered.

Nuclear fission power, possibly including thorium-based reactors,[30] would seem to be a logical candidate for accelerated growth to meet a rising domestic and world demand for energy. Support for this logic comes from renewed interest in new plants in the United States, plans in Asia for many new power reactors, and France's intention to begin to replace their many old reactors with new ones.[31] Relative to greenhouse emissions, it is only during the construction phase of nuclear plants, when large volumes of energy-intensive materials must be produced, that any greenhouse gases are produced as a net effect of using nuclear power. Increasingly, this conclusion appears to be creeping into the thinking of energy policy makers in diverse parts of the political spectrum.[32] On the other hand, several roadblocks, mostly political, lie in the way. In the United States and in many other countries, fear of anything "nuclear" or "radioactive" or of anything that has been "radiated" has resulted in lengthy plant licensing periods that make the cost of capital for new nuclear plants noncompetitive with those fueled by coal. This flies in the face of the critical medical benefits we draw from nuclear pharmaceuticals and nuclear diagnostic techniques, the fact that we are exposed to low levels of natural radiation continuously, and, increasingly, the reality that we are being protected by radiological technology for the detection of terrorist threats.

The same politics of fear that work against building new nuclear plants, as well as decades of ineptness on the part of the United States government and Congress, has caused the failure to provide either for recycling or disposal of the used highly radioactive fuel rods after their replacement in plant reactors. These spent fuel rods in fact represent a vast future resource of energy if they were recycled and their unused fissionable material extracted for use in new fuel rods. To be referred to as "waste" strains normal logic. None the less, because President Jimmy Carter stopped development of a civil sector recycling capability in the United States in the late 1970s – a capability that exists in France and Japan – the United States considers spent nuclear fuel rods to be just that: "waste." Temporary storage of 77,000 tons of high-level radioactive waste, mostly spent fuel rods now in more than one hundred water-filled ponds and dry storage sites near nuclear power plants, is nearing the physical and regulatory capacity of these locations. The government's preferred permanent, underground burial site in the Yucca Mountain facility in Nevada[33] continues to be unavailable due to political disagreements and legal challenges.[34] Safe, geological stabilization of nuclear materials has been demonstrated by nature in the case of natural fission reactors.[35] At this time, however, there appears little chance that a waste storage facility for spent fuel rods will be available by the target date of 2010, or that there will be any reconsideration of their reprocessing to reduce the amount that must be buried.

Additional issues confound the long-term prospects for nuclear power. They represent attractive targets for terrorists. In other parts of the world, they offer a means of producing weapons-grade materials that can be used in weapons of mass destruction. On the other hand, reactors in nations that support terrorism invite pre-emptive attack by the world's democracies.

Proposals for a high-temperature, high conversion efficiency Generation IV (Gen IV) reactor, part of the Department of Energy's 25-year plan, make up one of the hopes to resolve many of the real and imagined problems with fission power.[36] Considerations of Gen IV include an initiative for an Advanced Fuel Cycle that would reduce reactor waste by 90%. This could permit the United States to add nuclear power without needing a second waste repository. The plan, joined in by ten or more other nations, would be to make the reactors highly proliferation-resistant and to destroy (transmute) weapons-grade plutonium and other nuclear materials.[37] As ambitious and politically attractive as the Gen IV plan appears, only a small probability exists that it will be able to satisfy significant new demand before 2050. Thus, as with fossil fuels, we cannot count on nuclear fission power to play a major role in a global, eight-fold or greater increase in energy supply over foreseeable decades.

3.2.3 Terrestrial solar power

Strong advocacy exists and significant tax resources have been expended on behalf of the development and subsidization of terrestrial solar power in all its various forms. None of these methods of solar energy conversion, that is, "renewable" energy, has reached the level of "in the box" technology and markets that exists for fossil fuels and nuclear fission. Except for the issues of energy storage and efficient long-distance transmission,[38] which must be addressed before solar can be considered a major global contributor to meeting future demand, many believe that some solar technologies are close enough to full commercialization to be considered as near-term possibilities.[39]

Direct conversion of solar energy to electricity through photocells has found applications in space and remote locations where other sources of electrical power are either not cost competitive or have political drawbacks. (This is also the case for several types of small nuclear fission devices.) Some commercial and residential solar photoelectric arrays feed power into base load grids where subsidies are provided, energy storage is not an issue, and benefits in public opinion are realized by utilities. Steady progress in photocell conversion efficiency has been made over the last four decades. Some very high efficiency photocells, however, use toxic materials that will force limits on their exposure to fire and the environment. In spite of all this progress, significant doubt exists about the potential of direct solar energy to contribute to pre-2050 global energy supply.[40]

Without the benefit of taxpayer subsidies and efficient energy storage systems, the collection of solar energy to use as heat, that is, "solar thermal conversion," or to provide electricity also has found no broad commercial niche. As in the case of photovoltaic systems, many detailed technological thermal conversion issues related to exposure to natural environmental conditions (extreme heat and cold, dust, moisture, etc.) remain to be solved before broad-scale commercial applications will be cost effective. Further, if direct and thermal solar conversion systems ever reach the technological and net-cost level to warrant broad-scale application, the dispersed and intermittent nature of solar radiation will make land use issues increasingly important.

Stored solar energy in wood, peat, animal oils, and dung has been used for heat and light since the discovery of fire. Similarly, elevated sources of water provided mechanical energy through water mills for thousands of years. Since late in the twentieth century, other stored solar energy resources have been studied, including waves and thermal gradients in the sea. Lunar tidal energy systems have also been investigated. The only significant stored energy contributor continues to be hydroelectric systems, but such systems still only account for about 7% of world energy supply.

Technological use of stored solar energy has been subsidized by governments since the first large-scale development of sailing ships, windmills, and hydropower systems beginning in pre-history. Most recent emphasis in stored energy by the private sector has been on advanced wind turbine farms. Net, cradle to grave, cost analyses,[41] without subsidies and fully burdened with the cost of money, have indicated that large-scale wind systems may be cost-effective in some specific cases when their generated power feeds directly into existing power grids and does not exceed about 10% of a system's power. In this sense, they are a form of peaking power for those regions where wind speeds and consistent availability are appropriate. Wind energy generation is also popular with portions of the public and state regulators. In the absence of an efficient energy storage system, however, and with wind energy penetration above 10 to 15%, the intermittent nature of wind (low-capacity factor) results in increasing costs of providing backup energy sources such as new fossil fuel or fission power plants. With a geologically based, compressed air energy storage system available, and appropriate expansion of transmission capacity, wind energy may be cost-effective up to about 30% of an energy system that is suitably located, geographically. Increasing concern, on the other hand, is being expressed over the visual appearance of huge "wind farms" as well as over the deaths of increasing numbers of wild birds that are hit by the turbine blades. Further, subsidies may be losing favor – it appears that the government of Denmark, the world's largest producer of wind turbines, has withdrawn its subsidies for domestic use of this technology.

Unlike wind, direct and thermal solar conversion systems are far from being cost-effective in the absence of subsidies.[42] The dollar and net energy costs of manufacture, the lack of efficient storage systems, and inherently low conversion efficiencies seriously undermine the economics of such systems. Stand-alone systems of these three types are not close to cost-effective, as no large-scale, economical storage system has yet been demonstrated. Stored solar energy in ethanol made from grain is also not cost-effective without the subsidies currently provided by various governments.

Exceptions to the general lack of cost-effectiveness for solar systems exist in special geographic situations where access to other power systems is impractical or cost-prohibitive. With a concentrated and well-conceived research and technology development program, such as that briefly attempted by NASA in the mid-1970s,[43] various forms of solar energy could make significant contributions to meeting some regional energy demand growth. In the foreseeable future, however, terrestrial solar energy cannot be a major means of meeting the 2050 and subsequent demand for major new energy sources.

3.2.4 Conservation

Great progress has been made in energy conservation and conversion efficiency since the oil embargo of the 1970s. In spite of the growth in interest in conservation of energy, progress has not kept pace with the growth of consumer demand for more products that consume energy. Thus, even though automobiles get better average gas mileage and the price of gasoline in constant dollars is much less in 2004 than in 1974, most families have several cars rather than just one or two. A new, constant drain of electricity comes from home and business electronics and other modern technologies.

To a significant degree, however, a conservation ethic has replaced a consumption ethic and the holy grail of ‘‘sustainability’’[44] continues to receive worldwide attention. Too often, proposals for sustainability in energy would require either a massive decrease in living standards or equally massive increases in prices or taxes paid by consumers or a significant loss in freedom of choice. For now, without ‘‘unsustainable’’ expenditures on new energy, transportation, agricultural and other infrastructures, advocates of sustainable technologies must work to make them competitive in price, convenience, and desirability to technologies already in the marketplace.

More surely can be done in conservation and conversion efficiency, and a research and technology development partnerships between industry and government (see Chapter 1) would be cost-effective up to a point. Some of the technology areas that probably could benefit from such energy conservation, research, and technology partnerships are as follows:

- Industrial process heating[45]
- Commercial heating and cooling[46]
- Building and homes[47]
- Motor vehicles[48]
- Lightweight materials for transportation[49]
- Ethanol fuels[50]
- Fuel cells[51]
- Electric motors and pumps[52]
- Thermoacoustic technology[53]

- High-power density energy storage[54]
- Lighting.[55]

The competitive marketplace by itself continually provides strong incentives for manufacturers to improve the energy efficiency of existing and new products in the above areas. Further, government regulation of transportation, industrial facilities and power plants, and other sectors of the economy have forced additional responses by the private business sector as well as by consumers. Many of these actions are probably not cost-effective and certainly will have many unintended consequences.

As desirable as technological improvements related to energy conversion can be, conservation and conversion efficiency alone will contribute relatively little to meeting escalating global demand until they can compete independently in the competitive marketplace, that is, where consumers actually want to buy them. Some commentators also submit that conservation increases the difficulty of a transition to new energy sources by reducing the pressure on the reserves of fossil fuels,[56] although this seems to be an overly pessimistic suggestion and certainly not one with which most people would agree.

3.2.5 The "portfolio" approach

Many advocates exist for a "portfolio" approach to meeting foreseeable demands for new energy using a mix of forced conservation and "in the box" sources.[57] These approaches pick and choose various energy sources discussed above until their hypothetical numbers for availability match their predicted demand curve. Rarely do proponents include a significant "aspiration" demand increase in their projections of demand. Usually, these portfolios consist of combinations of conservation, efficiency gains, wind and other solar sources, and various "carbon free" sources to be adopted by the world as a whole. Some portfolios include nuclear fission as a carbon-free source to be considered.

The primary difficulty with the portfolio approach, in addition to underestimations of future demand, lies in dealing with the complexity of national and particularly international management of the development and oversight of the energy mixes outside the controls and constraints normally provided by a relatively free marketplace for energy. Adam Smith's "invisible hand"[58] remains the most efficient manager and arbiter of any definable segment of the civilization's market for goods and services. Energy is no exception.

3.3 "OUT OF THE BOX" ENERGY SOURCES

Only a few potential energy sources that fall "out of the box" appear worthy of additional consideration as possible contributors to energy demand by 2050 and beyond. These particular candidates are deuterium–tritium fusion, space solar energy, and lunar helium-3 fusion. Each is under current development or detailed consideration by the private sector or governments or both. Because the broad-scale introduction of hydrogen as a means of energy storage and transport requires sources of electricity or heat or a combination of these in excess of normal demand, it will be considered below as well. Each of these future energy sources should be viewed in the context that energy technologies currently in broad-scale use (discussed above) will be competitors during their initial development and implementation phases.

In the context of the management of large-scale, complex technical programs discussed in detail in Chapter 9 and summarized in Figure 3.1, bringing these unproven sources of large-scale energy supply to a point where they can be evaluated relative both to each other and to "in the box" energy options will require that certain conditions be met. It helps to compare the challenge of providing global and sustainable sources of energy to meet an eight-fold increase in demand to the challenge faced by the Apollo space program's generation of managers. For example, to have a sufficient base of technology to proceed with development, the existing base would need significant enhancement along multiple paths with clear and important decadal milestones. In fact, the development and demonstration of new energy sources will require several development paths, each of Apollo-like complexity and each with sub-paths of parallel development for critical functions and components.

The existing reservoir of young engineers and skilled workers would need to be augmented through restructuring of the elementary and secondary system of education in math and science. Broad private and federal funding of university-based science and engineering research projects needs to be provided so that the necessary pool of engineering and scientific talent exists when it is needed, which is now.

The current climate of national and international unease brought on by the potentially catalytic events of September 11, 2001, and the War on Terrorism should suffice to build and maintain political and financial support for government and private initiatives related to energy supply. An United States Administration committed to leadership in this arena, and the formation of competent and disciplined management teams for each energy path, of course, will also be critical to ultimate success in these endeavors.

KEYS TO PROGRAM SUCCESS

1969 APOLLO

Sufficient Base of Technology
WWII/Cold War/Eisenhower Decisions

Reservoir of Young Engineers and Skilled Workers
1957 "Sputnik" generation

Pervasive Environment of National Unease
Campaign of 1960

Catalytic Event that Brings Focus
Gagarin's Flight

Trusted and Persuasive Leader
John F. Kennedy

Tough, Competent and Disciplined Management
Post-Apollo 204 Fire

FUTURE ENERGY

Sufficient Base of Technology
Enhancement of Existing Base along Multiple Paths

Reservoir of Young Engineers and Workers
Fund University-Based Research
Improve Elementary and Secondary Schools

Pervasive Environment of Unease
Current Climate of Unease should Suffice

Catalytic Event that Brings Focus
September 11, 2001

Trusted and Persuasive President
Time Will Tell

Tough, Competent and Disciplined Management
?????????????????????

FIGURE 3.1 Comparison of the keys to the success of the Apollo program and those required for successful future energy supply development.

3.3.1 Hydrogen

Hydrogen often constitutes a useful means of storing and transporting energy where mass or power density is more important considerations than cost. Recent technical and political hype surrounding the potential of a "hydrogen economy,"[59] and the fact that other energy sources are required to produce it, makes some mention of hydrogen appropriate at the beginning of a treatment of "out of the box" energy systems. At the present time, any hydrogen used in petroleum refining, space missions, and a few other limited applications must be produced from or through the expenditure of natural gas by "steam methane reforming."

Sustainable, that is, non-fossil-fuel-based, large-volume hydrogen production will require scientific advances in photobiological, photoelectrical and other approaches to splitting water; large expenditures in research and technology development of production and conversion technologies; costly development of the infrastructure to carry hydrogen to consumers and store it safely prior to use; and a gradual, but still disruptive change in hydrogen-fueled systems available in the marketplace.[60] Heavy-handed and costly regulatory forcing of hydrogen use may be advocated if not implemented. If coerced or uncoerced consumer demand for hydrogen increases steadily in the next few decades, the use of excess and off-peak base load electrical power for water disassociation will be the most economical and environmentally friendly means of production.

A great deal more investigation, business analysis, and actual engineering must take place before we can reasonably assess the role of hydrogen in meeting pre- or post-2050 demand for energy. Nothing changes the fact that hydrogen is a form of energy storage, and that energy is consumed in its production and in its conversion to useful purposes. Photobiological and photoelectrical production, possibly assisted by the use of waste heat from other energy systems, would appear to be the long-term hope for a cost-effective hydrogen economy, at least for transportation systems.[61]

3.3.2 Deuterium–tritium fusion

Ongoing national and international research related to the possible commercialization of deuterium–tritium fusion power has concentrated mostly on magnetic confinement concepts, although hypothetical potential exists in the defense-related research on inertial confinement of these two heavy isotopes of hydrogen.[62] The principal focus of the international program in magnetic confinement fusion is the International Thermonuclear Test Reactor (ITER) project,[63] now projected to cost $10 billion in current dollars.[64] Valid skepticism exists, however, that the new cost goal can be maintained. Designed to reach fusion ignition (burning plasma) in a fusion reaction of deuterium and tritium, ITER has stalled over an international stalemate between Europe and Japan on where it will be located. In 2004, Europe even indicated that it might pull out of the planned collaboration in favor of building ITER in France.[65] ITER will predominantly be an experimental physics project rather than a practical engineering project and lies a long way from the prototype plant necessary to demonstrate commercial viability.

Although the emphasis on ITER has resulted in a major contraction of alternative fusion research funded by governments, several important efforts are still being pursued. One of these is the FIRE initiative at Princeton University that would focus on the physics and technologies related to a specific power plant design (ARIES–RS/AT).[66] Another includes the long-term power potential of inertial confinement fusion research, directed primarily toward the stewardship of the United States' nuclear weapons stockpile.[67]

The major hurdle that deuterium–tritium fusion must overcome before a commercial prototype can be built is in the development and engineering of materials that can withstand the intense flux of 14 MeV neutrons produced by this reaction. Those neutrons carry the energy of fusion into the walls of the reactor where their kinetic energy is released as heat. Circulating fluid in the walls would pick up this heat and use it to drive turbines that in turn drive electrical generators. Unfortunately, no materials are known that can withstand the damage produced by the neutrons for more than a few years. Current estimates are that any plant of this kind must be shut down roughly 25% of the time so that the damaged wall materials can be replaced.[68] This approximately 75% or less online performance (capacity factor) compares unfavorably with the more than 90% capacity factor for nuclear fission plants. Clearly, materials engineering constitutes a major area that requires emphasis in the expansion of the technological base for deuterium–tritium fusion.

The problems caused by neutrons do not end with the removal of the damaged wall material. Nuclear reactions in this material would cause it to become highly radioactive. Unlike the spent fuel rods of fission plants, this waste is not amenable to reprocessing, so burial becomes the only option for disposal. Indeed, a deuterium–tritium fusion plant would produce more radioactive waste per kilowatt-hour of power than would one of today's nuclear fission plants.

Other problems face the commercialization of deuterium–tritium fusion. The tritium fuel is radioactive and must be bred (produced) from lithium in fission reactors, a process that is costly in both dollars and energy. Construction and operating costs for large magnetic confinement fusion plants, and certainly for large inertial confinement plants also, will be high, but no reliable estimates of those costs yet exist. Until the technical feasibility and commercial viability of these plants has been demonstrated by government efforts, no path to private capital markets exists, as evidenced by the lack of electric utility interest or funding of the deuterium–tritium fusion effort. Finally, of course, the radioactive fuel and waste associated with deuterium–tritium fusion power plants will draw legal and political challenges from the antinuclear activists.

All of the above indicates that deuterium–tritium fusion will have great difficulty becoming a player in the pre-2050 supply picture and not enough time to do so.[69]

3.3.3 Space solar energy

Since the 1970s, tens of millions of dollars of federal, international, and privately funded study and analysis has been dedicated to concepts involving the placement of large arrays of photocells in space for the collection of solar energy.[70] On its face, the concept has much appeal. Russia even talks of reflecting solar light from space into their arctic regions, using very large mirror arrays.[71] In the more general concept, solar electric energy would be converted to microwaves and beamed to very large collection antennas on the Earth and from there fed into the power grid. Two variations on this theme have been explored: satellite solar power systems and lunar surface solar power systems. Implementation of either would require very large space construction projects. The satellite system would be built from components launched from Earth, possibly augmented by lunar materials. The lunar surface system's solar collector would be manufactured from lunar soil. Successful assembly, construction, and maintenance of the International Space Station (ISS), particularly its large photocell arrays,[72] support the overall technical feasibility if not the financial viability for these approaches.

Advances in efficiency and decreases in the cost per watt of photovoltaic solar cells obviously will be critical to the economic feasibility of space solar power. Gradual advances in this regard continue, however, cradle-to-grave analyses of the use of photocell arrays to generated electricity on Earth, much less in space, show that there is still a long way to go.[73] The potential exists for major breakthroughs in reducing cell-manufacturing costs and in increasing conversion efficiency by pursuing flexible, ultrathin, molecular organic solids. These materials also have the potential for self-assembly.[74]

Existing space law, primarily under the Outer Space Treaty of 1967 and the statutory and regulatory law of the United States (see Chapter 13), would allow either type of space solar power system to be built and operated. Federal advocacy in support of the project probably would be necessary if international legal or environmental questions are raised, particularly with respect to power beaming.

The two approaches to space solar power have been studied extensively; however, both are dependent financially on taxpayer support of the research, development, and initial operational activation of the first prototype system.[75] Until a large-scale prototype demonstration has taken place, and an "apples to apples" comparison to competitive energy sources has been performed, investors are unlikely to provide the necessary capital to create a truly commercial enterprise. Further, even with governmental support of a prototype, a major reduction in launch costs either to Earth orbit or to the Moon will be required before a return on investment is possible for private investors. At the present time, then, there is not an obvious path into the capital markets without major expenditure by governments.

3.3.4 Lunar helium-3 fusion

Lunar helium-3 fusion power represents a relatively new entrant into the twenty-first century energy sweepstakes.[76] Subsequent chapters, summarized here, will detail many of the technical, legal, and financial aspects of lunar helium-3 fusion as a possible source of twenty-first-century energy supply. The financial and technical envelope now can be defined into which a commercial lunar helium-3 fusion power option must fit if it is to be both a source of pre-2050 energy supply and a logical rationale for private support of a Return to the Moon. The financial envelope is constrained by reasonable costs of capital and debt, assumed to be about 20% and 10%, respectively. Technically, like other undeveloped energy sources, a prototype demonstration of a helium-3-fueled power plant will be required along with a financial and risk comparison against its competitors. In addition, definition of a clear means to significantly reduce lunar launch costs will be required, as will a detailed approach for producing helium-3 from lunar surface materials.

The primary advantage that lunar helium-3 fusion will have over other "out of the box" energy sources in the pre-2050 timeframe is a definable path into the private capital markets. This path is a consequence of the potential of several near-term applications for helium-3 fusion technology in existing markets, prior to reaching breakeven power levels.[77] These applications look as if they can provide early returns on investment as well as lead technically toward competitive electrical power production.

Although quantities sufficient for research exist, no commercial supplies of helium-3 are present on Earth – if they were, we probably would be using it to produce electricity today. A light isotope of helium-4, the familiar birthday balloon gas, helium-3 comes to the airless Moon as part of the "solar wind." Stirred continuously by meteor impacts, the nearly four-billion-year old rocky debris layer, subsequently referred to as "regolith," slowly accumulates helium-3 along with ordinary helium, hydrogen, carbon, and nitrogen.

Apollo samples collected in 1969 by Neil Armstrong on the first lunar landing have shown that helium-3 concentrations in many lunar soils are at least 13 wppb (weight parts per billion). Detailed analyses of lunar soil samples and other evidence indicate that helium-3 concentrations are probably between 20 and 30 parts per billion in undisturbed, titanium-rich soils. Twenty parts per *billion* may not seem like much; however, the value of helium-3 relative to the probable energy equivalent value of coal in 2010–2020 – estimated conservatively at $2.50 per million BTU – will be almost $40,000 per ounce! This compares with about $400 per ounce for gold at the beginning of 2005.

At $40,000 per ounce, 100 kilograms of helium-3 would be worth about $140 million. One hundred kilograms constitutes more than enough fuel to power a 1000-megawatt electric plant for a year when fused with deuterium, the terrestrially abundant heavy isotope of hydrogen. A plant of that capacity will fill the needs of a city about the size of Dallas or Adelaide for about one year. The production of 100 kilograms of helium-3 per year would require annual processing of about 2 square kilometers of the lunar surface to a depth of 3 meters. In turn, that annual rate requires hourly mining of an area about 28 meters square and 3 meters deep along with the hourly processing of the finest 50% of the mined soil (about 2000 tonnes) to extract its gases. This is not a high mining and processing rate by terrestrial standards and only requires two 10-hour mining shifts per day, 20 days out of each lunar month (about 27 Earth-days long).

Once the gases in the soil are extracted by agitation and heat, they can be separated from each other sequentially by cooling to near absolute zero, where helium-3 can be separated from ordinary helium using special membranes. Current estimates indicate that development of this lunar mining, processing, and refining capability and supporting facilities, once design and development began, would probably consume about $2.5 billion dollars of investment capital over about five years. Financial breakeven at a sales price of $140 million per 100 kilograms, including the costs of launching equipment to the Moon discussed below, would occur when about five miner–processors are in operation, which is expected to occur about five years from the start of initial production.

In addition to lunar mining and processing, two other major technical challenges must be met if the private sector, or government, or a partnership between both, is to be successful in a lunar resource endeavor. First, before any other related investments can go beyond funding conceptual design, helium-3 fusion technology must be developed and adapted to the production of competitively priced electricity. The ‘‘second generation’’ approach to controlled fusion power involves combining deuterium (D) and helium-3 (^{3}He). This reaction produces a high-energy proton (positively charged hydrogen ion) and a helium-4 ion (alpha particle). Some side D–D fusion reactions result in a low level of neutron production, minimized by optimizing the amount of excess helium-3 introduced into the reactor. These neutrons will result in a need to dispose of a small amount of low-level radioactive waste at the end of a 30- to 40-year plant life.

The most important potential advantage of the D–^{3}He fusion reaction for power production, as well as other applications, lies in its compatibility with the use of electrostatic fields to control fuel ions and the fusion protons. Additionally, protons, as positively charged particles, can be converted directly into electricity, through the use of electrostatic deceleration as well as other possible techniques. Potential conversion efficiencies of 70% may be possible as there is no need to convert proton energy to heat in order to drive turbine-powered generators.

The ‘‘third generation’’ approach to fusion power fuses helium-3 with itself and would eliminate all neutron-producing reactions and thus also eliminate all radioactive waste at the end of plant life. Nuclear power without nuclear waste therefore becomes the ultimate promise of lunar helium-3 fusion. The theoretically predicted reaction rate for fusion of helium-3 and helium-3 have been demonstrated in the laboratory, but the demonstration of significant numbers of helium-3 reactions with itself has not. Such a demonstration, however, appears to be only a matter of time and the ability to optimize the performance of existing electrostatic confinement research reactors.

D–^{3}He fusion power promises much lower capital and operating costs than its twenty-first-century competitors due to potentially less technical complexity, higher conversion efficiency, smaller size, no radioactive fuel, no air and water pollution, a major reduction in cooling water requirements, and only low level radioactive waste disposal requirements. Recent estimates suggest that about $6 billion in investment capital will be required to develop and construct the first commercial prototype of a helium-3 fusion power plant. The development program would pursue, in parallel, several fusion approaches optimized for helium-3 fuel, ultimately focusing on two approaches for a power plant demonstration "fly-off" before beginning prototype plant construction. In this scenario, financial breakeven at today's wholesale electricity prices ($0.05 per kilowatt-hour) could occur after five 1000-megawatt plants were on line, replacing old conventional plants or meeting new demand.

The second major development challenge is to have a much greater payload capability and much lower cost for Earth to the Moon launches than those planned by NASA. The Apollo Saturn V rocket remains the benchmark for a reliable, heavy lift Moon rocket, as I and 11 other moonwalkers can testify. Saturn Vs were, and remain, the largest rockets ever used, weighing 6.2 million pounds and developing 7.5 million pounds of thrust at liftoff. This huge booster could reliably launch 48-tonne payloads to the Moon at a cost of about $59,400 per kilogram (2005 dollars). A new, modernized "Saturn VI" rocket should be capable of launching 50- to 100-tonne payloads to the Moon at a cost of $3000 per kilogram or less. A number of considerations related to vast technological advances in the 40+ years since the Saturn V was designed and manufactured indicate that the necessary 20-fold reduction in payload costs can be accomplished with investment capital of about $5 billion. Critically, we know what we need to do this time, unlike 1960 when President Eisenhower began the Saturn project.

Many other issues would be approached by a private enterprise effort in ways very different from an effort managed by a government agency. For example, a private company will immediately want its lunar employees to be settlers, eliminating the costs for their return to Earth. Additionally, spacecraft will be specialized for the tasks of landing precisely at known resource-rich locations on the Moon rather than serving two or more masters, such as, the International Space Station *and* a Lunar Base, as envisioned by NASA. The private initiative will concentrate on lunar surface vehicles, highly mobile space suits, work facilities, and buried habitats that provide reliable, low cost resource recovery. All equipment will be designed for indefinite operational life, including embedded diagnostics, anticipatory component replacement, and ease of maintenance and refurbishment.

Development of side business lines would proceed quickly to improve profit margins and help pay off debt. These potential businesses include sale of hydrogen, water and oxygen by-products from helium-3 extraction as well as food and other materials produced on the Moon. Lunar exports would be shipped to customers in space, including those going on to Mars. Launch of consumables from the Moon's one-sixth gravity to space-based customers has a great competitive cost advantage over launch from the six times greater gravity of Earth. Further, the development of fusion technologies on Earth will create near-term business opportunities in medical diagnostics and treatment, transportation, weapons detection, and nuclear waste elimination (transmutation). Other opportunities will be possible through the sale of low cost access to space. These additional, launch-related businesses include providing services for government funded lunar and planetary exploration, astronomical observatories, national defense, and long-term, on-call protection from the impacts of asteroids and comets. Space and lunar tourism also will be enabled by the existence of low cost, highly reliable rockets.

In summary, the major parts of the economic envelope within which helium-3 fusion must fit as related to other twenty-first-century energy sources are: total development cost <$15 billion, competitive coal costs >$2.50 per million BTU, and payload costs to the Moon <$3000 per kilogram. It may be worth noting that a capital investment of less than $15 billion would be about the same as was required for the 1970s TransAlaska Pipeline[78] and the 1980s EuroTunnel.

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4

BOOSTER: MOON ROCKET ECONOMICS

4.1 INTRODUCTION

AT this point in the development of a Return to the Moon strategy, it is too early to fully define all aspects of the engineering designs and operational plans that will be necessary for success in such an enterprise. This level of definition must await the synergistic interaction of the initial corporate and engineering team that will form when adequate financing to begin the enterprise is available. It is possible, however, to outline many first-level, logical and experience-born constraints on the development of these plans. This chapter and Chapters 5 to 7 will discuss the overall economics of Moon rockets, helium-3 fusion, lunar helium-3 resources, and lunar helium-3 production, respectively, in relation to first-level technical, operational, and cultural constraints.

Any unsubsidized, private, lunar initiative will probably require a return on investment from the sale of lunar helium-3 fuel for terrestrial fusion power generation. Financial scenarios can be envisioned in which fusion power plant revenues can subsidize lunar fuel production; however, it is useful to plan on this aspect of the initiative being self-sufficient and providing its own return on investment. Additional returns will come from the sale of lunar by-products for use in space, other applications of helium-3 fusion technology, and services related to booster capabilities and lunar facilities (see Chapter 11).

4.2 THE SATURN VI

The cost of placing large payloads on the Moon will constitute the single greatest component of the total cost of obtaining lunar helium-3 fuel. A private corporation's requirements to minimize costs will force the re-creation of an Earth to Moon launch capability comparable to the Saturn V booster of the Apollo Program. Placing mining and processing machines on the Moon, and providing the additional mass of support equipment and consumables for a lunar settlement prior to its self-sufficiency, will require at least the 48,000 kg (105,600 lb) that the Apollo 17 Saturn V put on a lunar intercept trajectory (Figure 4.1). Twice the Saturn V capability will be desirable for increased efficiency in the activation of a lunar settlement. Past studies conducted at the University of Wisconsin-Madison indicate that a lunar resource initiative might require the payload costs to reach the Moon to be in the order of $1000/kg if helium-3 production is to provide an attractive, say 20%, return to investors.[1] This cost, however, is essentially the cost of rocket fuel at the present time[2] and represents a hypothetical lower limit on lunar payload costs. A target cost of $3000/kg may be more realistic if other spacecraft and operational costs are to be covered by a new generation "Saturn VI."

4.2.1 The Saturn V benchmark

The development of low-cost, heavy lift rockets will be one of a private, Return to the Moon initiative's largest single components of capital cost and investment risk. Clearly, a demonstration of the commercial feasibility of helium-3 fusion power must come before major investment capital would be available for new space boosters. The possibility of economical access to the Moon's resources must also be clear to investors. Fortunately, a logical initial benchmark against which the cost and risk of heavy lift

FIGURE 4.1 Apollo 17 Saturn V launch system and spacecraft during transport to its launch pad on the Mobile Launch Tower. The Vehicle Assembly Building stands behind. The Saturn V booster and spacecraft combination stands 364 feet tall. (NASA Photograph KSC-72PC-426HR)

rockets can be evaluated exists in the Apollo 17 Saturn V system (Figure 4.1) of the 1960s, including the two spacecraft that provided access to the lunar surface.[3] Those spacecraft were the 30,900-kg Command and Service Module and the 17,250-kg Lunar Module. This launch and lunar access technology base, in broad concept, is an attractive benchmark design for future planning because of its proven robustness, reliability, and relative forgiveness of failures as compared to today's large rocket technology.

The Saturn V remains the largest rocket ever used to put human beings in space, weighing 2.8 million kg (6.2 million lb) and developing 33 million N (7.5 million lb) of thrust force at liftoff. The taxpayer paid about $16.1 billion at 1969 rates to develop, build, and operate the Apollo Program's rockets and spacecraft between 1961 and 1969, including four test flights and the first two landings on the Moon.[4] $16 billion at 1969 rates translate into about $112 billion at 2005 rates[5] as today's equivalent of that initial capital cost. The marginal (recurring) cost of hardware and operations for the last flight in the Apollo series, assuming that about five launches per year could be accommodated, has been calculated to be about $2.7 billion at 2005 rates.[6] Assuming that the Apollo hardware and management systems were capable of five launches per year (six occurred between October 1968 and November 1969), and also assuming an annual cost of short-term operating capital of about 10%, this marginal cost per launch would have been about $3 billion today. Again, this amount includes the cost of manufacturing and operating two spacecraft as well as the preparation and launch of a three-stage Saturn V rocket. Thus, $2.9 billion at 2005 rates, represents a conservative estimate of the total, early 1970s cost of landing a mass of 48,000 kg on the Moon. This mass includes, of course, the necessary fuels for maneuvering payloads once the Saturn V had done its job, and the mass necessary to return a crew to Earth.

The above lunar landing costs calculate to a marginal cost of about $59,400/kg. It is probably safe to say that this number defines the *maximum* potential cost envelope for any future return to the Moon by a private initiative. Surely, having "been there and done that," we could do it again for no more than $59,400/kg. If the target cost is $3000/kg, however, then a reduction by a factor of 20 or so in Apollo launch and access costs will be required. This will be no small order, to say the least. On the other hand, a reasonable assumption can be made that a commercial endeavor to re-create, modernize, and augment the Apollo launch concept, as the basis for establishing and supporting a permanent lunar settlement, would be much less costly than for Apollo. Such an assumption rests on the following facts:

1. A target payload capability will probably be 100,000 kg to the Moon rather than the approximate 50,000-kg potential of the Saturn V. This doubling of payload, other costs being held hypothetically constant, would halve the cost per kilogram. (It also may be about the most

powerful rocket that can be safely launched without damage to common above-ground structures due to acoustical pressures.)
2. A new Saturn-based development will already have available the exact specifications that need to be met and the design and operational approaches that have worked in the past. This knowledge of engineering and operational history will permit an emphasis on manufacturing simplicity, operational reliability, and cost reduction that was not possible in the atmosphere of Cold War urgency.
3. After over 40 years, newer, but still proven technologies will significantly enhance the Saturn's performance and reliability without the cost of significant new research and development, just new systems engineering and tests. Remarkable advancements have occurred in the quality, reliability, and mass of structural materials, computers, electronics, guidance systems, automatic control, wiring, rotating machinery, embedded diagnostics, and many other relevant areas. These technologies also may enable cost-effective, partially reusable concepts to be incorporated in a new Saturn VI system design.
4. Long-term production and operations contracts will reduce the recurring costs of rocket and spacecraft production. This may turn out to be the single most important cost-reduction factor.
5. Modern computer-based techniques for engineering design, industrial production, and business management will further drive down design, manufacturing, and operational costs through increased productivity.
6. As for any successful commercial activity, the private initiative will be extremely focused. Business imperatives will be "design to minimum cost" for manufacturing and operations as well as "design to maximum reliability and longevity."
7. Cost incentives will encourage or require that a private initiative's lunar employees become settlers from the beginning of lunar operations, or very soon thereafter. Thus, for most human flights using the new Saturn VI system, the mass that would be allocated for return to Earth can be used for additional income-producing payloads to the Moon.

If these seven general cost-reduction measures for Saturn launches to the Moon each result in a 1.6 reduction on the Apollo costs, then the required total cost-reduction factor of approximately 20 will be met or exceeded.

4.2.2 Booster operational costs

If an initiative meets the \$3000/kg target for launch cost to a lunar resource or lunar surface facility customer, a launch rate of five per year for

100,000-kg payloads would give a total yearly direct cost of launches of about $1.5 billion. Each of the five launches would then have a direct cost of about $300 million. Included in this cost should be, roughly, a 10% gross margin to cover short-term interest as well as taxes, overheads, and retained earnings. Making the assumption that $5 billion would be the capital invested in the new Saturn system development, $1 billion in long-term interest charges also would need to be covered in the launch costs. This additional $200 million per launch – the development investors' 20% "rate of return" – would be the conservative cost of long-term capital to a venture of perceived high risk. Thus, as summarized in Table 4.1, *each* of the five annual launches has a fully burdened cost of $500 million, including $300 million for hardware and operations plus $200 million for long-term interest on capital. (Once the feasibility of fusion power plants has been demonstrated and the new booster system successfully tested, relatively normal financing charges should be available for rocket production and launch.)

Are the assumptions in Table 4.1 reasonable? Can a new Saturn VI system be built and launched on a recurring basis for $500 million of internal costs? Can this be done in a time frame eventually that is attractive to investors? Is $5 billion – against Apollo's equivalent $112 billion – enough to more than double the capacity of the Saturn system and develop new companion spacecraft that provide access to resource production on the lunar surface? These are, of course, questions that serious, long-term investors must eventually ask. Only time, initial capital investment, and

TABLE 4.1 Summary of costs per launch of a hypothetical Saturn VI booster (in $ millions).

Financial component	Capital	Cost of sales	Long-term at 20%	Short-term at 10%	Total
New Saturn development	5000 est.				
Cost of capital/launch (at 5 launches/yr)			200	–	
Each launch (at 5 launches/yr at $3000/kg)		300			
Cost/launch (at 5 launches/yr)					**500**

detailed design-cost studies will determine the answers for certain. On the other hand, the seven new approaches given above, and potentially others not yet considered, for creating a new Saturn VI system suggest that the $3000/kg payload cost target can be reached by competent and disciplined management in spite of the present lack of tooling for manufacturing.

Forecasting a factor of 20+ reduction in development costs relative to Apollo is aggressive but not unimaginable. The development of a Saturn VI in the early twenty-first century will be very different from the situation at the beginning of Apollo when many unknowns existed and many parallel design and operational paths had to be followed. Nor will other Apollo era costs burden the new effort, such as those of the Mercury and Gemini operational test programs included above as part of the total cost of Apollo. Finally, the many financial and managerial incentives that would drive a private initiative to Return to the Moon would significantly reduce the costs of Saturn VI development.

4.3 ALTERNATIVES TO A "SATURN VI"

Although an upgrade and modernization of the highly successful Apollo Saturn system represents a logical benchmark against which to plan a Return to the Moon, alternative approaches to comparable heavy lift need to be evaluated.[7] That evaluation should consider reliability, cost, operational complexity, and any other factors that would affect the economic viability of the lunar helium-3 fusion power enterprise.

4.3.1 Shuttle derived booster

The heavy-lift booster system that has received most attention in recent decades is the one that has been used in the Space Shuttle system.[8] This "Shuttle Derived Vehicle" (SDV) basically would substitute a non-reusable payload module for the Space Shuttle itself, but retain the three shuttle main engines and the two solid rocket boosters. Its payload to the Moon has been estimated to be between about 40 and 45 metric tonnes,[9] or about 90% of the Saturn V.

In evaluating the cost-effectiveness of the SDV concept, the same potential cost-reduction measures noted above would be applied, particularly the potential of long-term production commitments. Two primary technical difficulties with a SDV remain, however. First, as the Challenger accident in 1985 showed, solid rocket boosters are extremely unforgiving and their failure does not allow for recovery of a payload. On the other hand, solid rockets that are properly designed, manufactured, and operated, have a very strong overall reliability. Their use in combination with a Saturn VI benchmark design should be evaluated.

Second, the high-pressure, hydrogen–oxygen fueled shuttle main engines are technically complex and expensive to build and maintain compared to low-pressure, kerosene–oxygen Saturn F-1 engines. A private initiative will find the two objections to a SDV difficult to work through, but still worth looking into as compared to the Saturn VI benchmark.

4.3.2 Energia

The Russian Energia booster, designed to lift the now abandoned Baran space shuttle, is occasionally mentioned as a potential heavy-lift candidate. If all information necessary for an adequate evaluation can be acquired, the Energia should be considered as a Return to the Moon booster. On the other hand, having its redesign and manufacture outside the direct managerial oversight of either a private or a public initiative would seem to be a commercial showstopper.

4.3.3 Multiple expendable launch vehicles

The assembly of lunar payloads of 50–100 tonnes in Earth orbit using multiple launches of existing or future derivatives of expendable launch vehicles (ELVs) appears to be the booster approach toward which NASA's Moon–Mars initiative is leaning. Because of NASA's attention to this option, future evaluation of its commercial potential should be straightforward. A 100-tonne payload to the Moon, however, will require the placement of about 500 tonnes in Earth orbit. The largest ELV available in the United States today, the Boeing Delta 4 Heavy,[10] can launch about 25 tonnes to low Earth orbit, 5 tonnes to the Moon, or almost 20 such launches for each lunar flight of 100 tonnes. Although proposed upper stages for the Delta 4 Heavy might double these payloads, the cost and operational complexity of Earth-orbit assembly still would seem to be commercially prohibitive on its face, but much more needs to be known before a comparative evaluation can be performed.

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FUSION: HELIUM-3 POWER ECONOMICS

5.1 INTRODUCTION

A demonstration of commercially feasible helium-3 fusion power constitutes the first "long pole in the tent" that would make a private "Return to the Moon" financially feasible. Required investment capital cannot be attracted to the development of a new Saturn VI booster and other space-related hardware until investors are convinced that a clear path to commercial fusion power exists and that the fusion power market will support commercial demand for lunar helium-3. Fortunately, a reasonable probability has developed in recent years that these investment tests can be met.

5.2 POTENTIAL APPROACHES TO FUSION POWER

Options for controlled fusion power can be divided into three "generations" of approaches. The first generation consists of fusing the heavy isotope of hydrogen, deuterium (D), with itself or with an even heavier and radioactive hydrogen isotope, tritium (T). D–T fusion reactions produce neutrons with energies of 14.1 million electron volts (MeV) along with 3.5 MeV helium-4 ions (alpha particles). Research in D–T fusion currently focuses on defense-related "inertial confinement fusion" (ICF) of D–T pellets and "magnetic confinement fusion" (MCF) of D–T plasmas. Sustained ICF power plants would require D–T pellets to be heated and compressed symmetrically and repetitively by high-energy lasers or other sources of electromagnetic energy.[1] ICF research relates primarily to the US government's stewardship of nuclear weapons stockpiles. MCF, however, has been the US government's, and the world's, primary fusion energy research area, which is justified by an assumed potential for commercial power production.[2] Toroidal, very high intensity, magnetic confinement systems (Tokamaks) constitute the primary research thrust. Tokamak reactors will employ extremely high field strength magnets (15–20 tesla) to confine D–T plasmas and ensure that fusion temperatures and pressures are reached.

5.2.1 Deuterium–tritium fusion

Several characteristics that are inherent to D–T magnetic confinement fusion severely limit this approach's potential as a commercial power option, in spite of the world's focused attention. First, tritium is radioactive and this inherent hazard demands special handling precautions. Second, with neutrons as the primary reaction product carrying most of the fusion energy, conversion of D–T fusion energy to electricity requires a secondary heat cycle, as do fossil fuels boilers or nuclear fission reactors. This requirement limits the practical net thermal conversion efficiency to about 40%, although use of waste heat can slightly raise this efficiency. More critically, the conversion of the kinetic energy of neutrons to heat in the walls of a D–T reactor has two extremely adverse effects. On the one hand, progressive physical damage to the materials making up the reactor's first wall necessitates wall replacement every few years, resulting in a maximum online duration (capacity factor) of about 75%.[3] Further, the removed, metallic first wall materials are highly radioactive in the short term due to neutron-induced nuclear transformations and must be disposed of as high-level radioactive waste. Indeed, a greater volume of such waste is created per kilowatt-hour of D–T power than in existing fission power reactors.

Although D–D fusion reduces the disadvantage of containing radioactive tritium, it is an even less attractive option than D–T. D–D fusion reactions (which produce 3.65 MeV average energy per reaction compared to 17.6 MeV for the D–T reaction) have two equally probable reaction product lines, one producing a neutron and a helium-3 ion and the other producing a proton and a tritium ion. Secondary reactions between deuterium and tritium then produce additional neutrons so that D–D fusion actually produces more neutrons per kilowatt-hour than D–T fusion.[4] Theoretically, it might be possible to remove tritium from D–D plasma before it reacts with deuterium; however, no plausible mechanism exists to do this. Thus, D–D fusion may have only a marginally, but not dramatically, lower waste volume than D–T fusion.

The Tokamak approach to fusion power also comes with very high inherent capital costs. Technical complexity, conventional conversion efficiency, large size, radioactive fuel handling, and radioactive waste disposal will accompany and frustrate attempts to commercialize this fusion power option.[5] This even assumes that the engineering, physical, and international political issues confronting D–T magnetic fusion can be resolved by the $10-billion-plus International Thermonuclear Experimental Reactor (ITER) project.[6]

5.2.2 Helium-3 and deuterium–helium-3 fusion

The "second generation" approach to controlled fusion power involves combining deuterium and helium-3 (^{3}He).[7] The D–^{3}He fusion reaction theoretically produces a proton and a helium-4 ion with the proton having an energy of 14.7 MeV. In practice, some D–D reactions in the plasma produce neutrons at 2.5 MeV. These low-energy, secondary neutrons can be held to a few per cent of the total produced energy by lacing the fuel with excess helium-3 – a tack that would allow 40–50 years of plant operation before first wall removal.[8] Also, the removed wall material, after the decay of its short-lived isotopes, eventually can be disposed of as low-level radioactive waste comparable to waste produced in the practice of nuclear medicine.

An important potential advantage of the D–^{3}He fusion reaction for power production as well as in other applications lies in its compatibility with the use of electrostatic fields and various anode and cathode geometries for the control and acceleration of fuel ions. Further, most of the reaction's energy appears in the form of protons and helium-4 nuclei. These fusion products, as positively charged particles, can be converted directly into electricity. Net plant conversion efficiencies of 60–70% probably will be within reach as engineering research progresses.[9]

Technical complexity of a D–^{3}He fusion power plant relative to all existing base-load power plants, except hydroelectric, would be greatly reduced by the absence of a heat conversion cycle. Relative to D–T fusion plants, the absence of a tritium breeding blanket and radioactive fuel should shorten the licensing time for commercial plants. Further, the reduction of first wall ablation damage and induced radioactivity will add to the simplification of D–^{3}He plant design versus that for D–T fusion. D–^{3}He fusion concepts using electrostatic confinement also have the potential to reach sustaining fusion power[10] at inherently smaller plant size (volume and mass per kilowatt-hour) than current, base-load fossil fuel and nuclear fission plants or possible future D–T fusion plants. The potential exists for mobile, 50–100 MWe power plants that offer many options for more efficient delivery of electrical power as well as potential application in sea,[11] air, and space transportation.[12]

D–^{3}He fusion power therefore promises significantly lower capital and operating costs than its twenty-first-century competitors. This conclusion results from less technical complexity, high energy conversion efficiency, small size and potential mobility, no radioactive fuel, and only low-level radioactive waste after 50 years of plant life.

A third, ideal generation of fusion reaction, the fusion of helium-3 with itself, offers the potential to eliminate all neutron production and thus to have nuclear power without nuclear waste. ^{3}He–^{3}He fusion (Figure 5.1) produces two protons and a helium-4 ion (alpha particle) with a total energy of 12.9 MeV. Although the waste disposal savings and environmental advantages may end up favoring ^{3}He–^{3}He fusion, at this point in our understanding, it has not yet been determined if the total, purely economic tradeoff will favor ^{3}He–^{3}He over D–^{3}He for commercial fusion power generation because of the lower fusion reaction rates of helium-3 with helium-3 as compared to D–^{3}He and the higher cost of lunar helium-3 versus terrestrial deuterium.

Clearly, a great deal of research must be completed before any generation of fusion reactions can be fully evaluated as an energy source for a commercial electrical power plant. The best demonstration to date of D–T fusion, using a Tokamak device, has been a peak of 16.1 MW during a very short pulse in which the ratio of fusion power produced to total input power was 0.65. This occurred in the Joint European Torus (JET).[13] D–D and D–^{3}He steady-state fusion reactions (Figure 5.2) of about 10^8 per second ($\sim$0.001 W) are routinely achieved in a small inertial electrostatic confinement (IEC) research device at the University of Wisconsin–Madison.[14]

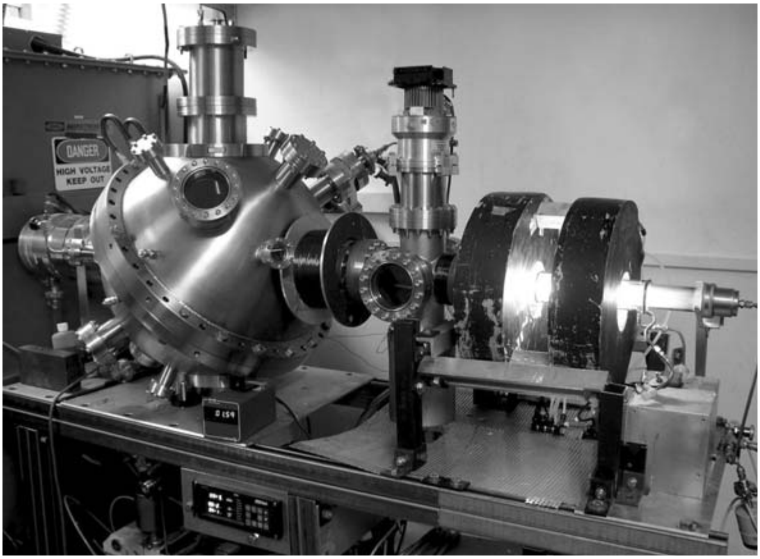

FIGURE 5.1 Experimental setup to demonstrate ^{3}He–^{3}He fusion. Spherical device on the left is 30 cm in diameter. (Photo courtesy of Gregory Piefer, University of Wisconsin–Madison Fusion Technology Institute)

5.2.3 Hydrogen–boron-11 fusion

The fusion of a hydrogen ion (proton) with a boron-11 (^{11}B) ion to produce three high-energy alpha particles (helium ions) has been examined theoretically. Also, the fusion cross-sections for this reaction have been measured.[15] This fusion reaction only approaches D–^{3}He reaction rates at significantly higher temperatures. Also, two facts make it difficult if not impossible to produce more fusion power from p–^{11}B than the plasma loses in bremsstrahlung radiation. First, p–^{11}B produces only 8.7 MeV of energy per reaction, compared to 18.4 MeV from D–^{3}He. Second, the charge (Z) of the boron ion is 5 and leads to extremely high bremsstrahlung radiation (scales upward as Z^2). Some people argue that the bremsstrahlung radiation problem can be overcome if the electrons that generate it can be held at a much lower temperature than the ions in the plasma. Creating such a temperature difference would be difficult because the collisional energy transfer between electrons and ions would then be large. This "hot-ion" mode in plasmas has not been successfully demonstrated.

It is known that p–^{11}B fusion has an advantage over D–^{3}He in fuel availability, that is, boron is easily available from certain minerals and brines on Earth. The other possible advantage of p–^{11}B is very low neutron production, because the main reaction produces no neutrons,

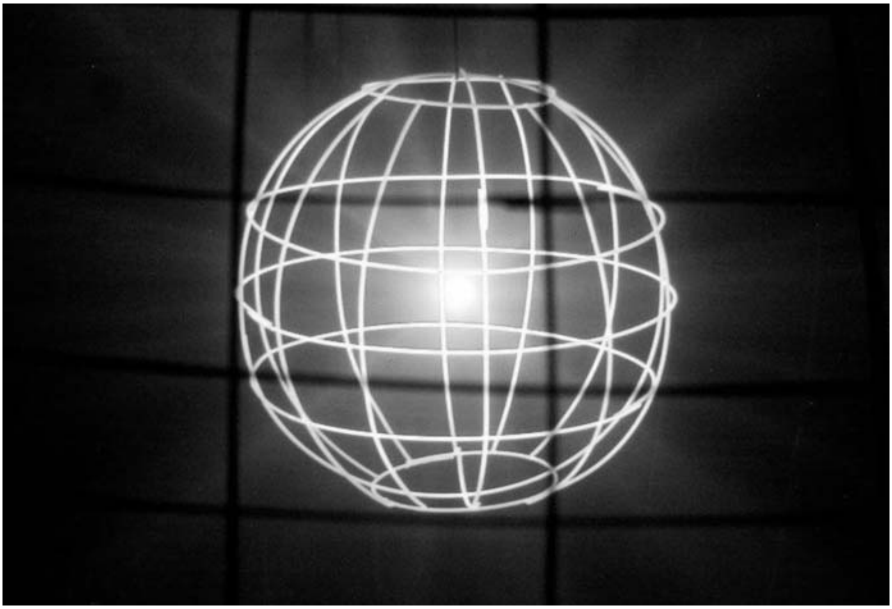

FIGURE 5.2 Steady-state D–^{3}He fusion reaction at $\sim 10^{8}$ reactions per second in an experimental inertial electrostatic confinement device. Glowing grid is 10 cm in diameter. (Photo courtesy of University of Wisconsin–Madison Fusion Technology Institute)

only alpha particles. At high energies, however, some p–^{11}B reactions produce a neutron plus one ^{11}C radioisotope. Another difficulty exists with p–^{11}B in most magnetic fusion configurations, where the fusion products slow down in the background plasma. Energies of the three alpha particles in the main p–^{11}B reaction channel are very high, and, as they slow down, they can produce radioactive waste products through the production of a neutron plus ^{14}N and a proton plus ^{14}C. The bottom line is that neutron production in p–^{11}B fusion, if feasible, may approach 1%, which is approximately that from D–^{3}He plasma if operated at a 3 : 1 ratio of ^{3}He : D.

5.3 ECONOMICS OF DEUTERIUM–HELIUM-3 FUSION

Strong arguments can be made that the fusion of deuterium and lunar helium-3, and potentially the fusion of lunar helium-3 with itself, can lower the cost of fusion power development, reduce the cost of electrical power to the consumer, and solve many environmental problems associated with electrical power production in general.[16] In making general technical comparisons between D–^{3}He fusion and D–T fusion, the dominant issues are fusion power densities (kWe/tonne of plant) of a burning plasma, magnets required for plasma confinement, heat fluxes on reactor walls, sustaining input power, fuel source, radiation damage to reactor components, radioactive waste disposal, and nuclear proliferation. With one possible exception, D–^{3}He fusion is inherently superior to D–T fusion in all of these categories. That possible exception is obviously "fuel source." D–^{3}He fusion will require recovery of helium-3 from the Moon whereas D–T fusion will require tritium-breeding blankets in the reactor walls. The cost tradeoff is between the in-reactor breeding and subsequent handling of radioactive tritium (T), the mitigation of first wall neutron damage, and the disposal of high-level radioactive waste on the one hand and, on the other, the cost of recovery of helium-3 from the Moon. Do the advantages of D–^{3}He fusion outweigh the cost of lunar fuel?

Although much engineering research lies ahead before there is a definitive answer to this question, the financial envelope into which that answer must fit can be closely approximated today. The value of lunar helium-3 for fusion electrical power plants on Earth will be a function of the cost of competitive energy sources. Residual fuel oil recently reached a price over $50 per barrel ($8.62/million BTU),[17] and nothing indicates that it will be significantly lower in the foreseeable future. At this price, the oil-equivalent value of 100 kg of helium-3 burned in the D–^{3}He fusion reaction (5.6×10^7 million BTU/100 kg)[18] would be about $480 million. If compared to the average price of residual fuel oil in the 1985–2000 period of about $3/million BTU,[19] 100 kg of helium-3's value would be $170 million, but it is doubtful if such a price for oil will be seen again.

Steam coal constitutes the future direct competitor to helium-3 for power generation.[20] Prior to 2004, steam coal prices were stable for almost three decades at about $1.27/million BTU or $26/ton. Helium-3's energy equivalent value relative to pre-2004 coal would be $71 million/100 kg. (100 kg of helium-3 is used here for comparison as that is enough, plus about 25% reserve, to service a 1000-megawatt electric (MWe) D–^{3}He fusion power plant for a year. This size plant would supply the electrical needs of a city with a population of a million persons for about a year.)

Steam coal prices for future contracts have begun to rise rapidly, up 60–70% in early 2004[21] with some recent sales at $3/million BTU. We can safely assume that coal will be at least twice as expensive as it was previously when helium-3 fusion begins to compete as a power source 10–15 years in the future.[22] As coal will remain helium-3's principal fuel competitor for the foreseeable future, a very conservative estimate of the energy equivalent value of 100 kg of helium-3 in 2010–2015 would be about \$140 million, equivalent to coal at \$2.50/million BTU. Therefore, a terrestrial sale price of \$140 million/100 kg, or \$105 million for a 75-kg annual supply to a 1000-MWe plant (75% availability or "capacity factor"), is a conservative target price at which helium-3 must prove to be a competitive fuel for electrical power generation. To examine this issue further, the economics of coal should be the benchmark against which to compare the economics of helium-3 power plants (Table 5.1).

Coal-fired power plants cost about \$1 billion for a 1000-MWe capacity,[23] indicating a cost of capital of about \$100 million/year. Plants of this size would pay about \$180 million annually for fuel at current contract prices and about \$360 million at \$2.50/million BTU, a probable price during the start of the competitive period in 2010–2015. Coal plants have annual operating costs of about \$44 million (about \$0.0044/kWhr).[24] This will make the total annual cost to run a 1000-MWe coal plant about \$504 million.

Because D–^{3}He fusion will be a new technology entering the power marketplace, the cost of capital for research and development will constitute a major early competitive cost factor relative to the mature technology based on burning coal. Much of the required technology for D–^{3}He fusion power development, however, has been demonstrated in other applications.[25] There are currently several candidate technical approaches to the implementation of commercial helium-3 fusion.[26] These include "inertial electrostatic confinement (IEC)"[27] and "field reverse configuration (FRC),"[28] – the latter concept offering potential operating advantages. Development of the best commercial approach (see milestones in Section 11.4) would probably begin with the funding of two or three accelerated but parallel experimentation efforts related to each of five possible technical approaches, and these research efforts would require a total finance of about \$150 million and three years of accelerated experimentation before a selection could be made of the two or three best avenues on which to proceed further.

This selection process would include studies of the manufacturing, construction, regulatory, and cost tradeoffs between the various design alternatives. Parallel demonstrations of fusion power breakeven and beyond ($Q \gg 1$) for the two or three selected approaches would require about \$1 billion in additional financing. Design and construction of a full-scale commercial plant, using the final approach selected and capable of being sold in the power-generation marketplace, would take a further, estimated, \$5 billion. Therefore, on a stand-alone basis the total development costs would be in the range of \$6 billion, probably available

TABLE 5.1 Power-related financial components of a privately financed lunar helium-3 fusion power initiative. (Amounts are in millions of dollars; "est." = estimated)

Financial component	Capital	Cost of sales	Long-term at 20%	Short-term at 10%	Total (annual)
Helium-3 coal equivalent value/100 kg					**140**
1000-MWe plant revenues (at $0.04/kWhr in 2005 dollars)					**320**
1000-MWe coal plant	1000				
Cost of capital				100	
Fuel costs ($2.50/$10^6$ BTU)		360			
Non-fuel costs		44			
Cost 1000-MWe coal plant					**504/yr**
Development 1000-MWe helium-3 fusion plant	5000 est.				
Cost of capital			1000		
1000-MWe helium-3 plant	500 est.				
Cost of capital				50	
Fuel costs		105			
Non-fuel costs		22 est.			
Cost 1000-MWe helium-3 plant (1st)					**1177/yr**
Cost 1000-MWe helium-3 plant (5th)					**377/yr**
Cost 1000-MWe helium-3 plant (15th)					**244/yr**
Gross income from power (after 15th plant)					**1140/yr**

at about 20% cost of capital. The development of commercial D–^{3}H fusion power in a time frame that will meet financial constraints and national and global needs will require a focused, Panama Canal–Manhattan–Apollo Project style of commitment and effort, in marked contrast to the current, leisurely international effort in magnetic confinement, D–T fusion research.

On the other hand, research, development, and testing of an operational design for a 1000-MWe helium-3 fusion power plant, or its equivalent of smaller plants, would probably be less than the $6 billion estimate due to earlier development of major portions of the necessary fusion technology base by several bridging businesses (see Section 11.3). The early businesses that apply fusion technology to the current markets will also hone the management, financial, and technical skills of the overall enterprise for the more challenging work ahead. In addition, retained earnings and cash flow from these precursor businesses are expected to allow significant amounts of internal financing of the more advanced technologies required for fusion power plants. For the purpose of this comparative analysis with coal-fueled power, therefore, it will be assumed that development financing will require about $5 billion in total and an annual cost of long-term capital of $1000 million per year (20%).

The delivered cost of electricity from fusion power plants using helium-3 would probably be significantly lower than that from a comparable coal-fired plant. Design and construction simplicity with roughly a factor of 2 higher energy conversion efficiencies would also lead to lower capital cost. A rough estimate for the cost of a 1000-MWe helium-3 fusion power plant would be half that of a coal plant, or $500 million, with an annual 10% cost of short-term capital of $50 million. In addition, many components of the coal-related non-fuel costs of $44 million will not be relevant to helium-3 fusion plants. For example, helium-3 fusion plants will convert the energy of protons and helium-4 nuclei directly to electricity rather than using inherently lower efficiency conversion of heat to electricity. There will be no emission issues and most environmental control costs will be absent, with the exception of the possible need to dispose of low-level radioactive plant components at the end of a 50-year or more plant life. As a first cut, therefore, non-fuel costs for a helium-3 plant will probably be about half the $44 million required for a coal-fired plant.

With the above assumptions, the annual costs for the first helium-3 fusion plant include a fuel cost of $105 million, an estimated $22 million for non-fuel costs, a cost of $1000 million for development financing, and a cost of $50 million for plant financing, totaling $1177 million. A 1000-

MWe helium-3 fusion plant could create annual revenues of about $320 million if its power were sold at $0.04/kWhr, which is a very conservatively competitive price well below the current wholesale electricity sale price. (This calculation also assumes that the plant has 80% availability (capacity factor), compared to 90% for most nuclear fission plants.) When the cost of development financing can be spread over five plants, the total annual cost becomes $377 million, which approaches financial breakeven. At the end of eight years, about 15 new plants would have customers providing revenues of over $1.1 billion. This rate of new, 1000-MWe power plant customers is about half the historical rate of the four new fission nuclear plants that came on line per year in the United States between 1973 and 1990.[29] It is several factors less than the penetration rate that occurred in France during that same period.[30] This analysis thus suggests that overall financial breakeven is possible for a lunar helium-3 fusion enterprise, including the potential to compensate for the possible early negative cash flow from lunar helium-3 production. If these estimates are reasonable, then lunar helium-3 fusion electrical power plants will be competitive in replacing old electrical plants and in providing new capacity to meet ever-growing twenty-first-century demand.

In this context, it should be remembered that the initiative's total income would be enhanced by sales of lunar helium-3 (Chapter 7) and would be augmented further by high margin sales both of resource by-products to customers in space and of space launch and flight services to scientists and tourists. On the other hand, success in driving launch costs down (Chapter 4) would reduce the differential between lunar and terrestrial suppliers of consumables for use in space. The value of lunar hydrogen, water, and oxygen in Earth orbit would be less than $600/kg, that is, a market price set by the new Saturn VI system's $600/kg for payloads launched from Earth to Earth orbit (~20% of the target $3000/kg for lunar payloads). Low launch costs, however, would expand the market for space travel.

5.4 SUMMARY

Clearly, the numbers produced by the preceding analysis represent a series of snapshots after a decade or so of business development activities. They must be refined and continuously updated relative to competitive energy prices. Indeed, all capital has been treated as ordinary debt rather than some or all being shareholders' equity, subject to different dynamics in the financial marketplace. Some of these dynamics can have the effect of reducing the outlay of cash in the early development years. None the less, this first conservative cut at those numbers is encouraging relative to the viability of a private lunar resource enterprise. The next step would be a more refined analysis that takes into account the realities of a 10–15 year complex development program (see Chapter 11). The fundamental technical keys to success are, again, the ability to create helium-3 fusion power plants, to operate a launch system with costs to the Moon of about $3000/kg, and to stay below $10 billion in development costs for helium-3 fusion power and a new booster system. Most importantly, economic viability of helium-3 fusion power in the terrestrial marketplace must be clear to investors before significant capital expenditures can made in accessing and producing lunar helium-3.

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6

RESOURCES: LUNAR HELIUM-3 ECONOMICS

6.1 INTRODUCTION

THE economic and technical chain tying lunar resources to commercial fusion power on Earth consists of three major links: (1) reliable low-cost payload transport to the Moon, (2) competitive helium-3 based fusion power plants on Earth, and (3) competitive helium-3 fuel costs. Payload costs and fusion power economics have been addressed in Chapters 4 and 5, respectively. The economics of the third link, competitive helium-3 fuel costs, depend largely on the costs of production and refining of lunar resources. Concentration or "grade" of helium-3 in the debris layer at the lunar surface generated by meteor impacts – the lunar regolith (Figure 6.1) – will largely determine those

FIGURE 6.1 View of largely undisturbed regolith in the Valley of Taurus–Littrow from the right window of the Apollo 17 Lunar Module Challenger. *The largest boulder in the near field is about half a meter in diameter and the base of the valley wall to the northwest is about 5 km away. (NASA Photograph AS17 147 22472)*

costs. That is, in what quantity and at what rate will regolith need to be mined and processed to obtain commercially significant resources?

The answer to that question begins with the pre-Apollo knowledge that fusion reactions in the Sun produce helium-3.[1] In contrast to the relatively low temperature and pressure chemical reactions that turn organic remains in terrestrial sediments into petroleum and coal, the extreme heat and pressure in the Sun fuse its hydrogen into helium and other elements. Ions of these elements stream away from the Sun with energies of 0.5 to 4 thousand electron volts per atomic mass unit (keV/amu),[2] following embedded magnetic lines of force. Positively charged hydrogen nuclei (protons) constitute 96% of the solar wind, helium ions 4%, and less than 0.1% each of carbon, nitrogen, and oxygen.[3] The ^{4}He/^{3}He atom ratio in the solar wind varies from 2283 to 2454, significantly lower than the ratio of ~2600 found in lunar soils (see below). The density of the solar wind averages about seven protons per cubic centimeter and increases to a few hundred protons and other ions during a solar flare or coronal mass ejection.[4]

The major by-product of any helium-3 production on the Moon will be large amounts of hydrogen. Hydrogen is present at measured levels of at least 50 to 150 ppm in the Apollo regolith samples.[5] Helium-4, nitrogen, carbon monoxide, and methane also comprise potentially important by-products, with total carbon measured at several hundred ppm in some samples and total nitrogen at around 100 ppm.[6] If helium-3 is extracted by heating the regolith to 700–800°C, some hydrogen will react with oxides and glasses in the regolith to produce water[7] at a ratio of about one water molecule to one hydrogen molecule.[8] Hydrogen ions (H^+) may replace those of sodium in the silicate mineral plagioclase[9] or become an interstitial H_2 molecule, or pockets of molecules, in glass or in the crystal structure of various minerals. One possible indication of continuous hydrogen replacement of sodium in plagioclase is the presence of a very thin, transient sodium atmosphere around the Moon.[10]

The flux of the solar wind ions impacting the Moon per unit area varies with the quantity ejected from the Sun and their interactions with the Earth's magnetosphere. As the Moon has no atmosphere, these ions hit the mineral and glass particles exposed at the surface. They penetrate up to a few ten thousandths of a millimeter beneath the exposed surfaces of individual grains.[11] In the 1960s, five teams of Apollo sample analysts predicted that solar wind volatiles, including helium-3, would be found concentrated in the lunar surface materials. The amount present would depend on the length of time that regolith had been exposed to space. Indeed, these teams reported at the First Lunar Science Conference in March of 1970 that they had extracted solar wind volatiles from Apollo 11 samples and analyzed their isotopic concentrations and ratios.[12]

Interest in lunar helium-3 remained purely scientific for about 13 years until, in 1985, researchers at the Fusion Technology Institute of the University of Wisconsin–Madison were investigating D–^{3}He and seeking potential helium-3 resources. They realized that the solar wind should have deposited helium-3 on the Moon and, while investigating how much may have been deposited, they became aware of the results of the earlier Apollo solar wind analyses. They immediately realized the significance of the Apollo discovery relative to future energy resources.[13] The fusion of helium-3 with deuterium and the production of protons and alpha particles had been demonstrated in 1949.[14] This potential source of fusion energy, however, had been virtually ignored as a practical option because of the absence of commercially significant quantities of helium-3 on Earth. Extremely small, commercially insignificant amounts of primordial helium-3 can be found in the helium mixed with natural gas and with gases emanating from mid-oceanic vents.[15] Amounts adequate for experimentation, however, are available at about $1,000/gm from the processing of the tritium used in nuclear weapons (tritium decays to helium-3 with a half-life of about 12.3 years) and normally can be purchased from the United States or Russian governments.[16]

6.2 GEOLOGY OF LUNAR HELIUM

6.2.1 General background

The lunar surface material or soil consists of debris derived from the underlying rocks (Figures 6.1 and 6.2) by eons of meteor impact and fits nicely into a category of geological material called "regolith."[17] The general rule for the concentration of solar wind volatiles in the lunar regolith is: The older (and deeper) the average regolith, the finer its average grain size, the greater its total exposed surface area, and the greater the amount of solar wind particles gathered. On the other hand, the actual amount of solar wind volatiles in the lunar regolith – that is, the balance between adsorption and induced losses – has been affected by many variables.[18] These include the following:

1. Unimpeded solar wind flux relative to lunar latitude and longitude.
2. Tilt of the Moon's axis relative to the ecliptic plane.
3. Non-ecliptic component of the solar wind velocity.
4. Diurnal temperature profiles experienced by the regolith as a function of latitude and topographic slope.
5. Rate of redeposition on the lunar surface of volatiles released by thermal cycling or meteor impact as a function of latitude and abundance of high-latitude cold traps.[19]
6. The abundance of various host minerals, agglutinates,[20] and breccia[21] fragments in the regolith.
7. Interaction of the Moon with the Earth's magnetosphere.
8. Flux of micrometeorites impacting the upper surface of the regolith.[22]

A definitive model of this overall process has not been published, much less a model for the dynamics that determine steady-state retention of volatiles in the regolith. Although such models will be important as an aid to long-term resource exploration, empirical knowledge of solar wind volatile concentrations has been gained from Apollo samples and remote-sensing data. This knowledge permits at least a first-order understanding

FIGURE 6.2 View of the surface of largely undisturbed regolith from about 75 meters from the Apollo 17 Lunar Module Challenger. *The* Challenger *is 7 meters high. (NASA Photograph AS17 134 20509)*

of the geological details of helium-3 distribution, estimates of the minimum size of its resource base, definition of production rates necessary to meet potential demand, and identification of areas of initial commercial production interest.

Micro- and macrometeor impact and major surface temperature changes between lunar day and night are of particular importance in determining the retained concentration of helium-3 in the regolith. The upper surface of the regolith is exposed continuously to these effects simultaneously with the capture of solar wind particles. In the case of temperature, the upper several tens of centimeters of the regolith are exposed to thermal cycling each lunar day, decreasing from a change of several hundred degrees Centigrade near the equator[23] to no change in the deep cold of permanent shadow near the poles. For most of the Moon, surface temperatures change from maximum to minimum by about 100 to –150°C. The direct effects of this thermal cycling are absent only in permanently shadowed, low-angle illumination areas near the poles; however, these areas are potential cold traps for some released volatiles.[24]

Acting as a constant, long-term space weathering process, the micrometeor flux modifies and stirs the upper few millimeters of the surface, melting, remelting, and "gardening" this surface zone. Over time, increasing amounts of nanophase, single domain iron particles, embedded in high silica and alumina glass coatings, form on the surfaces of exposed grains.[25] Nanophase iron appears to be formed by a combination of two processes, both the result of the very high temperatures produced at points of micrometeor impact. Volatilized impact melt generated at such points lose their more volatile elements to space with the remaining more refractory components redeposited as coatings on nearby grains. The coatings consist of high silica and alumina glass containing imbedded iron particles. On the other hand, high-temperature, point reduction of FeO in silicate impact melts containing solar wind hydrogen will also produce increasing amounts of nanophase iron.[26] The relative importance of these two processes has not been established and both are probably significant. A gradual, age-related optical darkening (browning) of the lunar surface is one result of nanophase iron formation. The patina so produced on exposed rock surfaces visually resembles the "varnish" of chemical weathering common to terrestrial desert climates (Figure 6.3).

Slightly larger, macrometeor impacts extend the impact gardening process slowly downward. The deeper gardening takes place at a declining rate because the number of impactors decreases exponentially with increasing size.[27] Gardening reaches a depth of about 1 cm in about one million years, about 5 cm in 100 million years, and about 6 meters in 4 billion years.[28] The ejecta blankets of macrometeor impacts, up to an impact energy that can form craters that just penetrate the local regolith, bury the surface zone and re-expose older regolith once again to the solar wind and micrometeor impact. On the approximately 3.8-billion-year-old surface of Mare Tranquillitatis,[29] 18 meters is the average maximum crater diameter that would today just penetrate the average 6-meter depth of regolith and expose fresh basaltic rock to the regolith-forming process.[30] Mine planning, however, would evaluate each crater that potentially would be encountered by lunar miners.

The process of regolith gardening, mixing, and thermal cycling causes some solar wind gases to be released as they are also being captured. Upon release, these now largely neutral species are exposed again to the solar

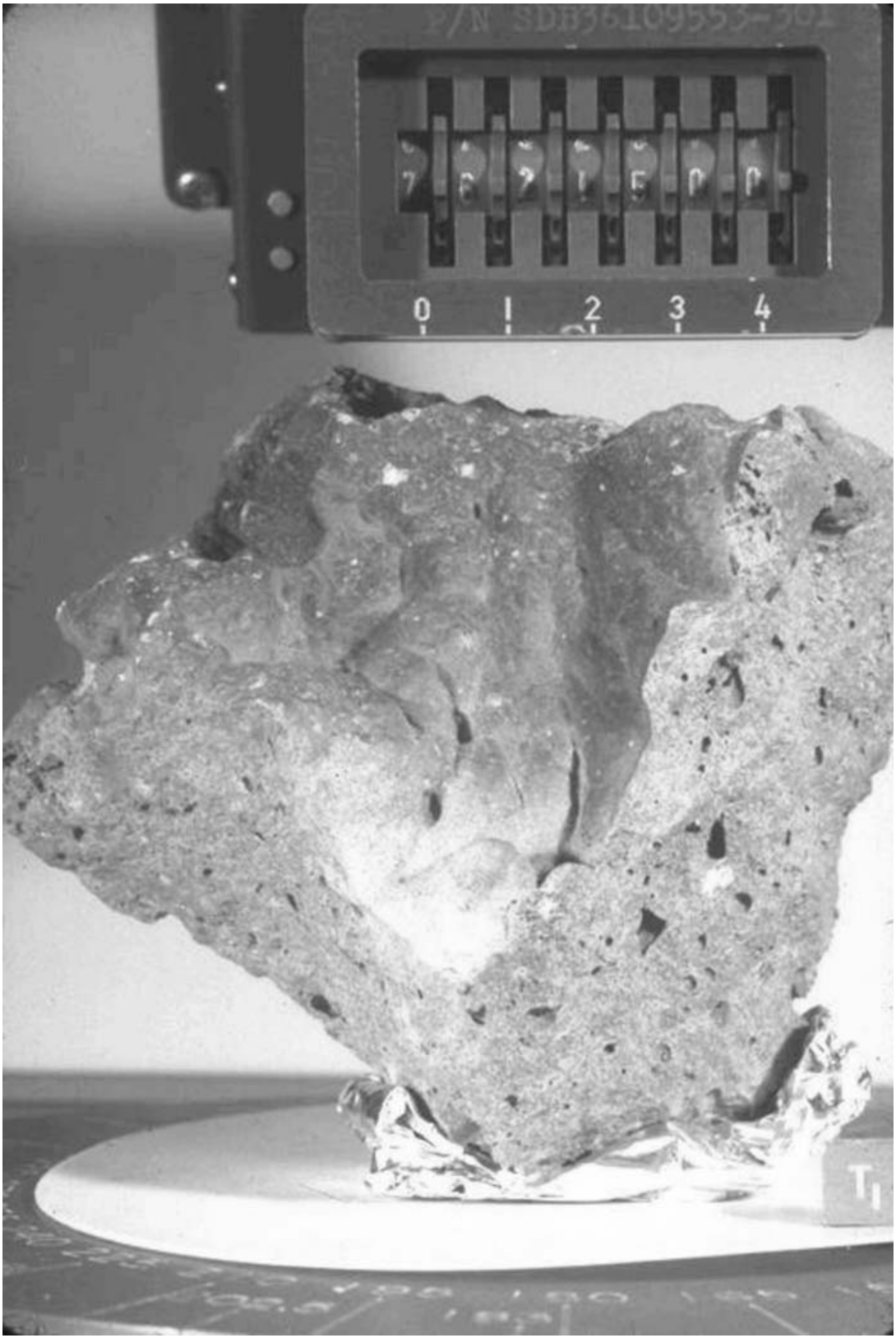

FIGURE 6.3 Glass and nanophase iron patina in large, open vesicle in impact melt breccia. Note fading of patina with depth in vesicle. (NASA Photo S72 56373)

wind. They are then re-ionized and are either lost to space or re-implanted elsewhere on the Moon. The gradual migration of some of these "pick-up" ions to colder average surface temperatures and permanently shadowed cold traps is probably the reason that hydrogen concentration in the regolith gradually increases by several factors toward the lunar poles[31] and away from higher average temperatures in lower latitudes. It is also likely that the concentrations of other solar wind volatiles increase poleward, but no measurements of their concentrations have yet been possible.

6.2.2 Helium-3 in the regolith

Undisturbed concentrations of solar wind volatiles in the lunar regolith have not been measured; however, some conclusions about their minimum and maximum average concentrations are possible[32] using lunar sample analysis data.[33] The most important baseline data in this regard comes as a consequence of Neil Armstrong's decision to fill the Apollo 11 rock box with 17 or more scoops of Tranquility Base bulk regolith. This bulk sample (10084), taken after Armstrong had loaded the box with a wide variety of selected samples, came from a 5 × 3 meter, irregular area beneath the right window of the Lunar Module *Eagle*.[34] Table 6.1 compiles the available helium-3 concentration data on the Apollo 11 regolith. In a few instances, published reports include only the amount of helium-4 and the ^{4}He/^{3}He ratio. In these cases, helium-3 concentrations have been calculated from the reported data but are included in a separate column in Table 6.1. The measured helium-3 content of 11 separately analyzed portions of loose fines from that bulk sample averages 11.8 wppb (weight parts per billion), ranging from 9.22 to 17.9 wppb.[35] Because of the evidence of losses of volatiles due to agitation discussed below, this concentration of helium-3 is probably close to the *minimum* possible bulk concentration in undisturbed regolith at the Apollo 11 site.

6.2.3 Helium-3 and titanium

All solar wind volatiles appear to be most abundant in the oldest and finest grained regolith samples.[44] Helium is additionally concentrated in the more titanium-rich regolith derived from underlying titanium-rich mare basalts.[45] In fact, the regolith concentration of helium correlates very strongly with the product of titanium and the regolith "maturity" as measured by the ratio of the magnetic intensity of nanophase iron to total FeO. The only significant lunar and regolith mineral that contains

TABLE 6.1 Helium concentrations in Apollo 11 regolith fines; that is, dust less than about 300 μm in diameter. (All but three samples are from 10084)

Sample	^{4}He wppm (“calc.” indicates only ^{3}He reported)	^{4}He/^{3}He mass ratio (atom ratio)	^{3}He meas. wppb	^{3}He calc. wppb
10010a[36]	19.6	3240 (2430)		6.06
10010b[27]	33.9	3390 (2540)		13.4
10084,18,I[37]	35.9	3400 (2550)	10.6	
	50.0 < 30 μm	3490 (2620)	14.3	
	7.98 min at 100–250 μm	3310 (2480)	2.41	
10084,18,II[28]	32.0	3400 (2550)	9.38	
	38.2 < 50 μm	3440 (2580)	11.9	
	min 8.64 at100–150 μm	3360 (2520)	2.57	
10084,29[38]	41.1	3390 (2540)		12.7
10084,40,1[29]	43.9	3490 (2620)	12.4	
10084,40,2[29]	40.2	3670 (2750)	11.0	
10084,47[39]	49.8 (wt ave.)	3360 (2520) (wt ave.)	14.8	
	221 < 1.4 μm	3110 (2330)	71	
	no min (decrease to 11.4 at 90–130 μm)	3330 (2500) [3490 (2620)] max at 15–42 μm)		
10084,48(1)I[40]	35.0 calc.	3224 (2418)	10.8	
10084,48(2)I[31]	39.5 calc.	3167 (2375)	12.5	
10084,48(5)I[31]	37.8 calc.	3003 (2252)	12.6	
10084,48[41]	34.0 25–42 μm	Not available		
	66.4 < 25 μm			
10084,59[42]	38.4 calc.	2851 (2138)	17.9	
10087,8[43]	34.1	3690 (2770)	9.22	
	76.1 < 5 μm	3610 (2710)	21.0	
	min 4.64 at 75–120 μm	3150 (2360)	1.47	

titanium is ilmenite, an iron–titanium oxide ($FeTiO_3$) that is particularly abundant in very old igneous rocks on Earth and their placer derivatives. Indeed, analysis of 10084,47 by size fraction shows factors of 2 to 3 or more concentration of helium-4 in ilmenite fines relative to comparable size fractions in the bulk sample.[46] Microprobe (helium) analysis of individual grains that compose the sample 10084,31 show a strong correlation between titanium content and helium concentration in this sample.[47] In regolith sample 75081,72, ilmenite concentrates from the 35–

54-μm size fraction have a helium-4 concentration of 25.3 wppm, 2.8 times that of the 35–54-μm bulk fines.[48] Helium-4 concentrations in ilmenite as much as 5.6 times that of bulk fines are present in this same size fraction from other Apollo 17 regolith samples not derived from titanium-rich basalt. This relationship probably holds for all size fractions as the titanium content shows no correlation with grain size.[49]

It would seem that, relative to other minerals and glass, the close-packed, hexagonal crystal structure of ilmenite[50] reduces, relative to silicates, the loss rate of helium due to thermal cycling. Ilmenite's refractory nature[51] also may reduce losses during micrometeor impact melting. Further, investigation of terrestrial ilmenite crystals, bombarded with helium ions at solar wind energies, duplicated the thermal release profile of helium from lunar regolith samples.[52] The crystallographic controls for helium retention in ilmenite, however, have not been determined. In this context, as ilmenite constitutes the only significant oxide in samples of lunar regolith from all Apollo sites, it cannot be said with certainty that the presence of titanium alone controls the helium concentration. Helium retention may be primarily due to the inherent crystal structure of this class of oxide mineral.[53] None the less, titanium concentration provides an excellent surrogate for helium concentration. Titanium distribution at the lunar surface can be estimated by remote spectrometric analysis from Earth[54] or from lunar orbit[55] (Clementine[56] and Lunar Prospector[57] missions, fusion of those two data sets,[58] and data from other orbiting sensor systems[59]). Such analysis provides an important resource exploration database. The average TiO_2 content of 10084 regolith is 7.5 weight%.[60] Elsewhere in Mare Tranquillitatis, remote sensing indicates that TiO_2 contents as high as this or higher are present over many thousands of square kilometers of regolith.[61]

6.2.4 Regolith breccia vs regolith fines

Other data, compiled in Table 6.2, indicate even higher concentrations than the minimum average of 11.8 wppb estimated above for helium-3 in undisturbed regolith. Of particular interest are the regolith breccias, that is, masses of regolith indurated (compacted) to varying degrees by processes associated with meteor impact. The average measured helium-3 content of 14 portions of eight Apollo 11 regolith breccias is 12.7 wppb, ranging from 4.38 to 18.5 wppb.[62] These data indicate that the rapid impact-induced induration of regolith seals in at least 57% (18.5 vs 11.8) more helium-3 than is preserved in the Apollo 11 fines. The differences between the helium-3 (and helium-4) contents of regolith and the regolith breccias strongly suggests that agitation of the samples of regolith fines from their undisturbed location on the Moon, through the many handling steps on the way to the laboratory, has resulted in a significant loss of solar wind volatiles. Hydrogen/helium ratios also indicate losses due to agitation, with hydrogen lost significantly more readily than helium – that is, H/He atom ratios in Apollo 11 regolith fines measured in the laboratory are about 7.5, whereas the solar ratio is about 17.[63]

TABLE 6.2 Helium concentrations in Apollo 11 regolith breccias

Sample	^{4}He wppm ("calc." indicates only ^{3}He reported)	4He/^{3}He mass ratio (atom ratio) measured	^{3}He meas. wppb	^{3}He calc. wppb
10018[27]	42.9	3530 (2650)		12.2
10021[28]	16.2	3690 (2770)	4.38	
10021[27]	66.1	4400 (3300)		15.0
	[54.9] (9)			[16.1]
10021,20[34]	66.6	3920 (2940)	17.0	
	92.6 <5 μm	4050 (3040)	22.9	
	min 4.54 at 120–200 μm	3160 (2370)	1.43	
10023[27]	44.6	3430 (2570)		13.0
10027[27]	26.8	3910 (2930)		6.86
	[22.5] (9)			[5.28]
10046,16[34]	35.7	3910 (2930)	9.13	
10048[27]	37.5	3470 (2600)		10.8
10061[27]	83.9	4540 (3400)		18.5
	[71.1] (9)			[20.5]
10061,38(1)I[31]	61.2 calc.	3364 (2523)	18.2	
10061,38(2)II[31]	47.3 calc.	3491 (2618)	13.6	
10061,38(4)II[31]	57.5 calc.	3704 (2778)	15.5	
10061,11[34]	45.5	3970 (2980)	11.5	
	101 <25 μm	3880 (2910)	26.3	
	min 1.56 at >120 μm	2610 (1960)	0.60	
10068[27]	44.6	3707 (2780)		13.0

One also can conclude from these differences that both loosely held and firmly held sites for helium exist in the regolith, a conclusion supported by the broad 300–800° helium thermal release peak shown by sequential thermal release measurements on lunar fines.[64] The broad release peak may be related to variation in the energy of solar wind particles. Additionally, some loosely held sites might be associated with the thin glass deposits on individual grains, whereas the firmly held sites may be in mineral crystal structures and small aggregates of grains welded together with impact glass (agglutinates).[65] Although the Apollo 11 samples provide the best suite for illustrating the concentration differences in solar wind volatiles between loose fines and regolith breccias, comparison of fines and breccias from Apollo 17 confirm these differences (see Table 6.3), particularly in the less than 20-μm size fraction.

TABLE 6.3 Helium concentrations for Apollo 17 regolith fines and regolith breccias [location information[66]]

Sample	^{4}He wppm	^{4}He /^{3}He mass ratio (atom ratio)	^{3}He meas wppb	^{3}He calc wppb
Regolith fines				
70051,17 (1) regolith near LM	26.9	3830 (2870)		9.4
75061,21 (2) regolith on Camelot rim	19.3 27.4 <20 μm min 2.39 at >200 μm	3490 (2620) 3680 (2760) 2950 (2210)	7.38 9.91 1.08	
75081,32 (1) regolith on Camelot rim	28.9	3760 (2820)		10.2
75081,72 (2) regolith on Camelot rim	32.9 38.4 <20 μm min 3.40 at >200 μm	3610 (2710) 3590 (2690) 3160 (2370)	12.2 14.3 1.44	
Regolith breccias				
79035,15 (2) on van Serg ejecta blanket	33.6 48.4 <20 μm min 3.29 at >200 μm	3760 (2820) 3960 (2970) 3130 (2350)	11.9 16.3 1.40	
79135,32 (2) at van Serg rim	23.1 47.0 <20 μm min 4.77 at 54–75 μm	3990 (2990) 4030 (3020) 2960 (2220)	7.73 15.6 2.15	

6.2.5 Helium concentration vs grain size

Further indications that the concentrations of volatiles of undisturbed regolith are significantly higher than measured in Apollo samples[67] are offered by consideration of analyses of the composition of Apollo 11 and other regolith fines as a function of grain size fraction. For example, as shown in Table 6.1, the finest size fraction, <50 μm, of 10084,18 shows the helium-4 and helium-3 concentrations to be 27–35% and 19–39% greater, respectively, than the sample as a whole.[68] In the analysis of 10084,47 grain sizes less than 1.4 μm, the helium-4 and helium-3 concentrations reach 221 wppm and 71 wppb, respectively.[69] Similarly, analysis of 10087,8 grain sizes less than 5 μm shows the concentrations to be 76.1 wppm and 20.1 wppb, respectively.[70] These results almost certainly reflect the increase in surface area with decreased grain size fraction. On the other hand, helium-4 and helium-3 concentrations in 10084 reach minimum at about 150 μm that are, respectively, 78–83% and 77–84% lower than in the <50 μm fraction. These concentrations then increase in the coarser factions. Table 6.1 data also show a correlated decrease in ^{4}He/^{3}He mass ratios[71] with increased grain size fraction in regolith fines, changing from about 3500 to about 3300 before increasing in the courser fractions.

Similar relationships between grain size fraction and concentrations and ^{4}He/^{3}He ratios exist in regolith derived largely from basalt at the Apollo 17 site in Taurus–Littrow (Table 6.3). Apollo 17 samples 75061,21 and 75081,32 show the helium-4 and helium-3 concentrations in fine fractions of regolith to be 17–41% and 17–34% greater, respectively, than the samples as a whole.[72] Helium-4 and helium-3 concentrations in these Apollo 17 samples reach minimums at about 150 μm that are 89% and 91% lower than in the <20-μm fraction before again increasing in the coarser factions. Apollo 17 ^{4}He/^{3}He ratios also follow the Apollo 11 patterns.[73]

A final decision on the maximum grain size to process for helium-3 will be the result of more detailed analysis of concentration as a function of grain size evaluated against the way in which the complexity and cost of separation vary as a function of grain size. The information available to date suggests that the cutoff will be about 100 μm, but, if this is shown to be cost-effective, it will be desirable to be able to "tune" this cutoff to a maximum extraction efficiency per tonne of regolith mined once actual production begins.

6.2.6 Agitation losses

Two factors probably contribute to the decrease in helium with increasing size. First, and most obvious, the larger size fractions have less surface area than the smaller. Second, agitation affects the intermediate size fractions more than it affects the very fine and relatively coarse fractions. Lower mass, and therefore lower collision energies of agitated particles in the very fine fractions, may reduce losses. No obvious explanation exists to explain the increase in helium concentrations in the largest regolith size fractions; however, no similar increase is observed in crushed regolith breccias subjected to analysis by grain size fraction.[74] This difference further indicates that agitation has occurred during and after the sampling of regolith fines. Crushing of the breccias to produce size fractions, on the other hand, may have resulted in some agitation losses. As with regolith fines, there is a systematic decrease in the ^{4}He/^{3}He ratios with increasing grain size in crushed breccias.

Systematic variations in ^{4}He/^{3}He ratios between fines and breccias and between various grain size fractions also suggest that losses have occurred due to sample agitation. Although strong indications exist that the undisturbed concentrations of both isotopes of helium in lunar regolith are significantly higher than those measured for regolith fines in samples returned to Earth, there appears to be secondary enrichment of helium-4 relative to helium-3 in regolith modified by impact processes. In the fines from the Apollo 11 bulk sample (10084) in Table 6.1, the average of nine measured ^{4}He/^{3}He mass ratios is 3310. If two analyses of other regolith fines from 10010 are averaged in, the mass ratio is 3290. In the <50-μm size fraction of mature regolith fines, the average for three analyses of 10084 is 3470.[75] In the regolith breccias, however, the average of 11 portions of seven samples is significantly higher, reaching 3750, with six portions measuring above 3650, two of which have ratios of 4400 and 4540, respectively. Similarly, ^{4}He/^{3}He ratios for the <20-μm size fractions of two disaggregated regolith breccias (79035,15 and 79135,32) are 10–12% higher than the <20-μm size fractions of Apollo 17 basalt regolith fines – that is, 3960 and 4030, respectively, versus 3680 for the bulk fines.[76] Crushing experiments on breccia 10046[77] also show that the most easily released helium is significantly enriched in helium-4 (^{4}He/^{3}He mass ratio = 5000 for easily released helium vs ~3470 in the <20-μm fines of 10084).

Differences in ^{4}He/^{3}He ratios also exist between non-mare regolith samples 76321,2 and 76501,12 from Apollo 17.[78] The ^{4}He/^{3}He ratio for the <20-μm size fractions of regolith from the ejecta blanket of a 10-m diameter crater (76501,12) is about 7% higher than in the <20-μm fraction of apparently more mature regolith (76321,2) nearby. This apparent enrichment of ^{4}He associated with impact ejecta and with regolith breccias suggests that ^{4}He is more readily mobilized near the impact point relative to ^{3}He and is added to breccia and ejecta now present outside this point. The previously discussed decrease in ^{4}He/^{3}He ratios with increasing regolith grain size, however, seems to confirm that helium-4 is lost preferentially during sample handling and therefore probably also near points of impact. Reference to regolith samples 10084,18, 75061,21, 75081,32, 72501,14, 76321,2, and 76501,12 and regolith breccia samples 79035,15 and 79135,32 in Tables 6.1, 6.2, and 6.3 shows a 15–59% drop in the ^{4}He/^{3}He mass ratio with increasing grain size, with some reversals of this trend in the 200–300-μm fraction. A decreasing total surface area with increasing grain size, resulting in a decrease in the total loosely held helium in glass coatings, may be the reason for the reversal. Further, helium-4 from the decay of uranium and thorium in larger particles possibly may be contributing a non-solar wind source.

There is no obvious explanation for the differential loss of helium-4 and helium-3 during agitation and impact, with helium-3 being held more firmly. Helium overall, on the other hand, appears to be held more firmly than hydrogen, as indicated by a H/He atom ratio in regolith breccia 10073 of 4.8 versus the ~7.5 in the regolith fines.[79] Preferential loss of helium-4 relative to helium-3 is contrary to expectations related to depth of ion penetration as a function of mass and to diffusion studies on lunar samples.[80] Helium-3, as a lower mass solar wind ion than helium-4, would be expected to have less penetrating power into ilmenite crystal lattices than helium-4 and thus less retention when agitated. Diffusion studies of helium-3 and helium-4 in ilmenite also indicate a higher diffusion rate for helium-3; however, an experimental procedure could not fully duplicate natural solar wind helium implantation.[81] The explanation may be related to differences in the crystal chemical bonding of helium-3 and helium-4 atoms within the substructure of the glass coatings and the lattice and defect structure of ilmenite.

It is possible to estimate the amount of secondary helium-4 introduced into the breccias.[82] The corrected primary helium-4 value for 10061 is 71.1 wppm, giving a revised calculated value for helium-3 of 20.5 wppb (71.1 wppm/3470), using the average value for ^{4}He/^{3}He in <50-μm fines. Similarly, recalculated helium-3 values also are shown in brackets for breccias 10021 and 10027 in Table 5.2. The maximum correction (for 10061) indicates about a 10% higher helium-3 concentration in undisturbed Apollo 11 regolith, that is, ~20.5 wppb. This in turn indicates that at least 42% of the helium-3 may have been lost to agitation (20.5 vs 11.8 wppb average in the regolith fines). (It should be noted that Apollo core samples were obtained by rotary-percussive drilling. Analyses of regolith fines from these cores[83] are also suspected to have lost loosely held volatiles.)

Other laboratory and geological observations indicate that a large proportion of solar wind volatiles contained in the regolith can be released by agitation. Release of hydrogen, helium, and N_2 or CO during vacuum shearing of lunar fines has been reported.[84] Also, field evidence suggests strongly that the light mantle material partially covering the floor of the valley of Taurus–Littrow explored by Apollo 17 is the result of a gas-fluidized avalanche of regolith from the side of the 2100-m-high South Massif.[85] Release of volatiles through agitation during downslope and runout movement of a lunar regolith avalanche is a logical source of the fluidizing medium. This release is further suggested by the low total helium content of 14.0 wppm (average of three samples) in avalanche material ("light mantle") relative to 18.7 wppm (average of four samples) in non-avalanche regolith fines on the side of the North Massif.[86]

6.2.7 Summary

Considerations of the geology of helium-3 in the lunar regolith strongly indicate that the undisturbed concentration of Apollo 11 helium-3 – that is, the helium-3 subject to recovery through mining and processing of titanium-rich areas of Mare Tranquillitatis – is significantly higher than the 11.8 wppb average measured in Apollo 11 samples. Volatiles sealed into some regolith breccias indicate that the undisturbed concentration may be as high as 20.5 wppb. This difference, as well as consideration of $^4He/^3He$ ratios as a function of grain size, indicates that losses of helium-3 from Apollo 11 fines due to agitation may be at least 42% of the concentration in undisturbed regolith.

6.3 ECONOMIC GEOLOGY OF LUNAR HELIUM-3

6.3.1 General background

Economic geologists – who study the value, quantity, and origin of mineral deposits – use the terms "measured," "indicated," and "inferred" to distinguish resources that are at decreasing levels of certainty in terms of available tonnage at a specified value (see Figure 6.4).[87] Exploration, drilling, and sample analysis, or other direct means, have delineated "measured reserves" to the extent that further investments of capital for actual production are warranted. Of course, such investments only will be made if the value and tonnage, or volume, make economic sense in the time frame that the resource can be sold in a forecasted market. "Indicated resources" have enough geological definition to be included in long-term mine planning but will require additional investment in quantitative exploration before they can become defined as measured resources ready for production. "Inferred resources" are based on geological inference but are too speculative to be included in planning until further exploration takes place.

The current economic and geological position of lunar helium-3 in the titanium-rich portions of Mare Tranquillitatis is shown in Figure 6.4. Relative to the figure, upward, positive economic change in lunar helium-3 will be determined by increases in the cost of alternative sources of terrestrial energy, particularly coal. Downward, negative economic change would be caused by higher than anticipated lunar development costs. Increases in geological certainty could arise from direct sensing of helium-3 from orbital spacecraft; however, it definitely will come from detailed mapping and the fusion of all pertinent geochemical and geotechnical data prior to mining.

The first consideration an economic geologist makes relative to a potential resource must involve its estimated value, against which the costs of production can be weighed. What is the likely price per unit that can be realized in the marketplace at the point in the future when the production operations begin? The value of lunar helium-3 for fusion electrical power plants on Earth will be a function of the demand and supply of competitive energy sources. As already discussed in the previous chapter (Section 5.3), helium-3 will be in direct future competition with steam coal for power generation. Forecasting coal prices in the 2010–2015 time frame will be important to evaluating the competitive value of lunar helium-3. Prices for thermal or steam coal in Asia (4% of world demand, rising at 10% annually) have begun to rise rapidly, up 70–80% in 2004.[88] In fact, some analysts expect steam coal to reach and hold over \$2.50/million BTU in 2005.[89] Spot prices have approached \$2.00 in the United States for the eastern stoker coal in 2004.[90] Therefore, forecasting coal prices of at least \$2.50/million BTU, appears to be a reasonable planning assumption for 2010–2015.[91] This gives a conservative estimate that the energy equivalent value of 100 kg of helium-3 in 2010–2015 would be about *\$140 million*.

6.3.2 Mining analysis

With this value of \$140 million/100 kg in mind, how much helium-3 is reasonably available in the richest (highest grade or concentration) known portions of the lunar regolith? Working with the Wisconsin Fusion Technology Institute team in the 1980s, the late Professor Eugene Cameron,[92] one of the world's foremost economic geologists, made the

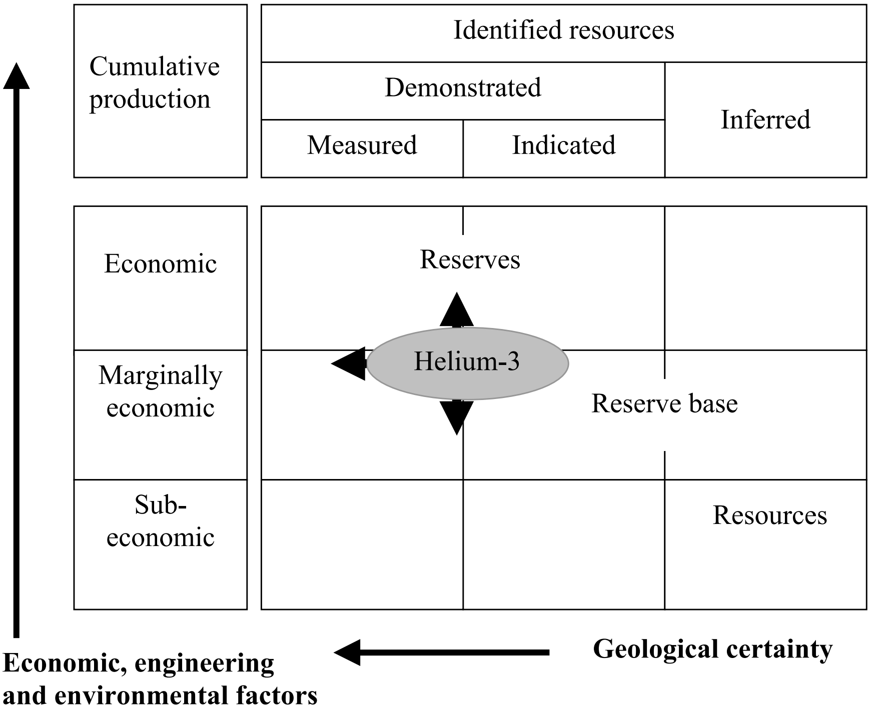

FIGURE 6.4 Current position of lunar helium-3 in titanium-rich portions of Mare Tranquillitatis relative to demonstrated economic potential. (Graphic background courtesy of P. J. Brown, University of Wisconsin–Madison)

first estimates of the quantities of helium-3 expected to be present in titanium-rich regolith on the Moon. Cameron, using available spectroscopic data on titanium concentration as discussed in Section 6.2.3, determined that the highest grade area for helium-3 totaled about 84,000 km^2 and another 195,000 km^2 of medium grade concentrations all within Mare Tranquillitatis. By geological inference, using photogeological mapping and remotely-sensed titanium concentrations, this is the region to which Apollo 11 samples apply, as well as those provided by Apollo 17. Cameron also studied the distribution of craters and estimated that about 50% of the 84,000 km^2 would be minable by the Wisconsin Mark II miner (see Section 7.2.2). If mined to a depth of 3 meters with a helium-3 concentration of 20 wppb (Section 5.2), this highest grade area would yield about 2500 tonnes of helium-3. In 2010–2015, with coal at $2.50/ million BTU, this amount of helium-3 will probably have an energy equivalent value of about $3.5 trillion! Even at 2003's contract coal prices, the value would be about $1.75 trillion. This economic potential, and the policy and environmental advantages of helium-3 fusion, have been exciting enough to keep the interest of the Wisconsin group and the author since the late 1980s.

Since Cameron's initial work, as discussed above, the helium-3 resources in Mare Tranquillitatis have moved close enough to being "measured resources" to warrant investment in the integrated analysis of all available sample and remote-sensing data. Cameron based his analysis on Apollo 11 sample data, the available spectroscopic definition of titanium distribution, and 1960s Lunar Orbiter photography.[93] Apollos 15, 16, and 17 metric and panametric cameras, operating from orbit, gathered additional high-resolution and stereophotography of the area of interest in Mare Tranquillitatis. Subsequently, two additional data sets obtained by the Department of Defense and NASA promise to further refine our knowledge of the distribution of titanium in that region's regolith. Respectively, these data came from optical spectrometers aboard the Clementine mission in 1994[94] and from the neutron and gamma-ray spectrometers of the Lunar Prospector mission in 1998–1999.[95] Further, improved optical specrometric data from Earth have been collected.[96] As discussed above, nanophase native iron accumulates in the regolith as a function of exposure to micrometeor impact, so remotely-sensed concentrations of such iron measure the length of exposure to solar wind and, in turn, indirectly measure relative helium-3 concentrations. This accounts for the strong correlation between both titanium oxide concentration and regolith maturity.[97]

It may be possible, as well as desirable to potential investors, to directly map helium-3 distribution in the regolith. This could be done on a global scale by developing an advanced gamma-ray spectrometer for a special-purpose, low-cost lunar orbiter, mapping the 20.6 (and higher) MeV gamma-rays released when a helium-3 nucleus captures a solar cosmic-ray-induced neutron.[98] (Significant *in-situ* understanding of neutron flux at the lunar surface was gained by the lunar neutron probe experiment deployed on Apollo 17.[99]) Telerobotic rovers could accomplish more specific and higher resolution mapping of a targeted mining site, albeit at significantly higher cost than an orbital sensor. The cost, however, of either an orbiter or surface rovers should not be incurred until the existing data sets are fully exploited and the need for one or the other becomes clear.

Although a major project that fuses all the available data sets is clearly necessary, there can be little doubt that very interesting concentrations (grades) of helium-3 are present in the upper 3 to 6 meters of Mare Tranquillitatis regolith. Based on analyses of Apollo samples to date, the average, undisturbed concentration of helium-3 in major portions of Mare Tranquillitatis appears to be at least 20 wppb, and conceivably higher. Analysis of drill cores from Apollo 15, 16, and 17, even though they have been depleted in volatiles by agitation and are highly variable from one buried ejecta blanket to another, indicates that this average grade will continue to a depth of at least 3 meters and probably to the base of the regolith.[100]

If a "recoverable" grade of 20 wppb helium-3 is assumed, the extraction of an annual shipment of 100 kg of helium-3 will require the mining of about 2 square kilometers of regolith to a depth of 3 meters. As summarized in Table 6.4, this annual rate is based on hourly mining of 2200 cubic meters or 750 square meters of surface area (28 × 28 meters). About half of the mined regolith, the <100-μm fraction, would be separated and processed for volatiles. A conservative work cycle has been calculated to achieve this rate, as follows:

- 13 lunar months per year
- 13 earth days as a mining month (sunlight period only)
- 20 hours per day as a mining–processing period, and
- 12 hours work per day for each mining–processing team (two hour overlap), six days per week.

Within this work cycle, several options exist for significantly increasing production rates as operations become settled and maintenance requirements are defined by experience. Such options include:

- Earth-light or full lunar night mining–processing,
- 24 hours per day mining with three 10-hour shifts, or
- seven days per week, three separate mining–processing teams, and staggered days off.

6.3.3 Mining–processing costs

Until specific design of mining and processing equipment can be performed, actual production costs for the annual helium-3 production rates given in Table 6.4 cannot be determined. The financial envelope into which these costs should fit will be discussed in Chapter 7. Definition of the architectural and engineering design parameters for a lunar settlement and for associated mining and processing facilities would build on existing space and terrestrial experience rather than experimenting with new, untested concepts. The primary areas of deviation from past experience in space will be in designs related to:

(1) minimum cost and maximum reliability
(2) the lunar dust and radiation environments
(3) the need for indefinite functional life for lunar facilities and equipment
(4) minimum feasible Earth-launch mass requirements
(5) maximum use of robotic and telerobotic systems and embedded diagnostics
(6) support of ancillary activities such as research and tourism
(7) minimum operational interaction with personnel on Earth, and
(8) anticipation of permanent settlement.

Design deviation from terrestrial mining experience will be in the areas of:

(1) integration of optimum human and robotic functions to minimize the number of workers required on the Moon

TABLE 6.4 Economic geology of helium-3 for Mare Tranquillitatis (MT = million metric tonnes)

Parameter	Apollo 11 value	Assumed value
Measured ^{4}He/^{3}He mass ratio (ave.)	3470	
Max. concentration ^{3}He in impact indurated soil	20.5 ppb	
Area of max. remotely sensed TiO_2 ($>7.5\%$)	84,000 km^2	
Probable minable area of max. ^{3}He (from TiO_2)	42,000 km^2	
Assumed depth of mining		**3 m**
Assumed recoverable ^{3}He from fines (ave.)		**20 ppb**
Regolith <100 μm	50%	50%
Mass regolith fines processed/100 kg ^{3}He		**5 MT**
Regolith specific gravity (ave. g/cm^3)	1.7	1.7
Mass regolith mined/yr/100 kg ^{3}He	10 MT	
Assumed mass regolith mined/yr/100 kg ^{3}He		**10 MT**
Assumed vol. regolith mined/yr/100 kg ^{3}He		**5.9×10^6 m^3**
Assumed area mined/yr/100 kg ^{3}He		**2 km^2**
Mined mass/hr/100 kg ^{3}He (max-13, 10-day mos, 20-hr days)		3846 tonne
Mined volume/hr/100 kg ^{3}He (max-13, 10-day mos, 20-hr days)		2262 m^3
Area mined to 3 m depth/hr/100 kg ^{3}He (max-13, 10-day mos, 20-hr days)		754 m^2 28 × 28 m
Processed mass/hr/100 kg ^{3}He (max-13, 20-day mos, 20-hr days)		1923 tonne
Processed volume/hr/100 kg ^{3}He (max-13, 20-day mos, 20-hr days)		1131 m^3

(2) minimizing support costs
(3) minimizing equipment mass, and
(4) flexible expansion of production based on the market demand for helium-3.

Each 100 kg of helium-3 will require the processing of about 10 million tonnes of regolith, that is, the working of 2 square kilometers of lunar regolith to a depth of 3 meters. Such bulk tonnage mining and processing is well within the practical experience of coal, rutile, ilmenite and diamond production.[101] Engineering of an actual regolith mining–processor, however, will be a new adventure for the mining equipment industry.

Start-up capital costs for a private lunar resource initiative promise to be significant in comparison to those associated with the new booster system and helium-3 fusion power plants discussed in Chapters 4 and 5, respectively. The initial objective of the first lunar operations will be to produce 100 kg of helium-3 per year for the first 1000-MW deuterium–helium-3 fusion power plant on Earth. (The actual requirement for such a plant is about 75 kg per year; however, a target production rate of 100 kg will provide flexibility in risk management and in marketing.) Costs for developing a commercial lunar miner–processor and associated facilities, with duplicate units to be manufactured under long-term production contracts, would probably be in the range of $1 billion, requiring about $200 million annually as the cost of long-term capital. Additional development costs may be financed as part of the development of fusion power technology if this estimate of $1 billion proves to be insufficient.

Development costs related to lunar helium-3 production would depend on the following:

1. The degree to which existing large tonnage miners can be re-engineered for lunar applications.
2. The new design engineering required to enable on-site processing of lunar volatiles.
3. The adaptability of proven space habitat designs to lunar applications.
4. The complexity of Moon *to* Earth launch systems.
5. The complexity of other lunar surface support hardware and software.

Overall production costs will include many other considerations, particularly the cost of placing payloads on the Moon. As will be discussed in the next chapter, the financial envelope into which all such costs must fit will establish the primary constraints on a viable, business enterprise based on lunar helium-3 fusion power.

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    1. ^{4}He(measured) = ^{4}He(primary) + x
    2. ^{4}He/^{3}He = 4540 (measured mass ratio for breccia)
    3. ^{4}He(primary) = ^{3}He(primary)(3470)(mass ratio for $<$50-μm fines)

    Subsituting in (1):

    4. ^{3}He(primary)(3470) + x/^{3}He(primary) = 4540

    Simplifying:

    5. 3470 + x/^{3}He(primary) = 4540

    Thus:

    6. x = (4540 – 3470) ^{3}He(primary)

    Solving by estimating that ^{3}He(primary) = 12.0 wppb, the average of eight non-enriched breccia values after eliminating one anomalously low value for 10021:

    7. x = 1070(12.0 wppb) = 12.8 wppm as the estimated secondary helium-4 in breccia 10061.
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7

SETTLEMENT: HELIUM-3 PRODUCTION ECONOMICS

7.1 INTRODUCTION

PRODUCTION of helium-3 and other resources on the Moon will require a permanent base of operations on the lunar surface even with a high degree of automation of various mining, processing, and refining activities. Individuals, groups, and the United States government have studied the establishment and operation of lunar bases since the mid-1960s.[1] In addition, there exists the foundation of technical and operational experience in space from Apollo, Skylab, Mir, Spacelab, the Space Shuttle, and the International Space Station. Relevant experience on Earth includes supporting terrestrial resource production in geographically isolated locations and supplying remote settlements and polar research stations. Use of this experience, with the appropriate perspectives on its applicability, will be highly beneficial to establishing cost-effective production operations related to helium-3 and other resources at a lunar settlement.

For a largely privately financed initiative, primary focus on business rather than policy issues will require deviation from past experience in space in matters related to the following:

- provision for minimum cost and maximum reliability;
- human, agricultural and equipment protection from the lunar dust and radiation environments;
- assuring indefinite life for lunar facilities and equipment[2];
- use of increased payload mass from a Saturn VI booster to increase equipment reliability and decrease cost;
- provision for efficient and highly reliable robotic and telerobotic systems;
- application of embedded diagnostics and reliable lifetime prediction of system components;
- support of ancillary activities such as research and tourism;
- minimization of operational interaction with personnel on Earth; and
- initiation of permanent settlement.

Principal deviations from terrestrial mining experience will be in the areas of:

- integration of optimum human and robotic functions to minimize the number of workers required on the Moon while maximizing reliability of critical operations; and
- development of minimum mass, highly reliable equipment that can operate continuously and indefinitely.

On the other hand, many aspects of lunar operation will be similar to those encountered by terrestrial mining activities, particularly in the continuous preparation and processing of large ore tonnages, the separation of valuable by-products, having a flexibility for production expansion based on market demand, and the management of a remote "company" town. Overall, the best practices of corporate governance and management should be followed (Chapter 11).

7.2 MINING, PROCESSING, AND REFINING

7.2.1 Mining strategy: spiral vs rectilinear

Two strategies for mining, processing, and refining the lunar regolith have been considered conceptually by the team at the University of Wisconsin. These strategies can be generally referred to as a "rectilinear strategy"[3] and a "spiral strategy."[4] The rectilinear strategy (Figure 7.1) has its roots in traditional bulk tonnage mining of deposits of relatively disaggregated materials on the Earth's surface. In the case of the lunar regolith, this strategy involves the definition of rectangular mining blocks that fit between young, blocky crater ejecta blankets, and the back and forth mining of those blocks along parallel, 11-meter-wide, 3-meter-deep cuts (see Section 7.2.2). Material mined would be conveyed into the miner–processor by a bucket wheel. Fragments greater than ~100 μm (~50% by mass) would be rejected to the sides by sequential sieving, and the remaining fine material would be moved into the volatile extraction unit. Extracted volatiles would be put into large tanks for transport to a central

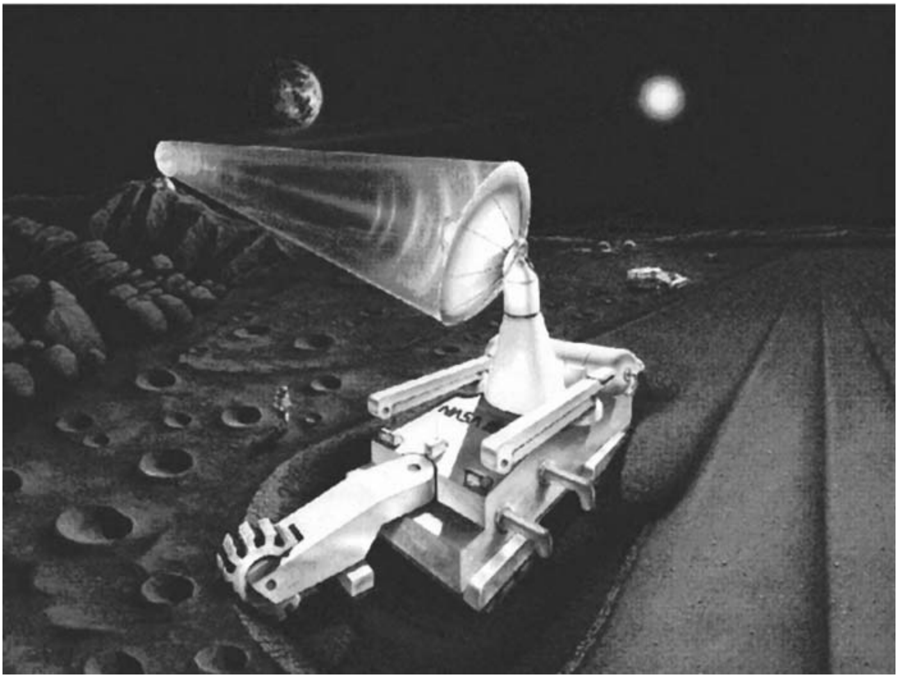

FIGURE 7.1 Artist's concept of the Mark II Miner–Processor operating in a rectilinear mining mode. (Courtesy of the University of Wisconsin–Madison Fusion Technology Institute)

refining plant away from the active mining area. Using this rectilinear strategy, estimates of the minable area in Mare Tranquillitatis range from 28 to 57% of the total with a probable average of 40%.[5]

An alternative, spiral strategy (Figures 7.2 and 7.3) offers a possible means to increase the overall efficiency of mining, processing, and refining of the regolith. Spiral mining's conceptual roots lie in large-scale, terrestrial open-pit mining with some conceptual heritage from circular irrigation systems. This approach involves the placement of a miner–processer unit at the end of a telescoping arm that is attached to a periodically mobile central station. Mining and processing would take place in an outward spiral using power supplied from the central station with volatiles being extracted from the regolith and piped to the central station for refining. Refined components would either go into temporary storage near the central station or be directly transported from the station to users. The central station includes refining, power, control, mobility, and habitation components and would be moved each time the telescoping arm had reached the practical limit of operation, estimated to be about 1 or 2 km. This would be equivalent to about two to six years of 100 kg/yr helium-3 production after each move.

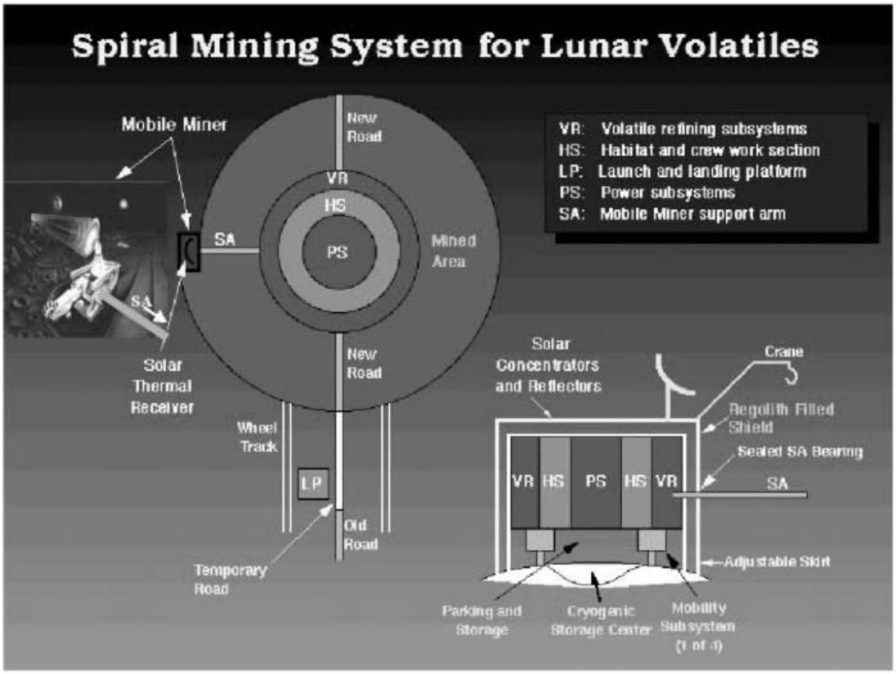

FIGURE 7.2 Spiral strategy to mining, processing and refining lunar volatiles. (Courtesy of the University of Wisconsin–Madison Fusion Technology Institute)

FIGURE 7.3 Regional application of the spiral strategy to production of lunar volatiles. (Courtesy of the University of Wisconsin–Madison Fusion Technology Institute)

Determination of the most cost-effective means of shipment of products from the Moon, however, must await studies comparing rocket launch with electromagnetic launch. Long-term storage on the Moon might be in inflatable containers placed in nearby craters and covered with insulating regolith. A tradeoff study between active or passive long-term cooling of stored volatiles also will be needed.

A spiral strategy would appear to allow more flexibility than a rectilinear one for the following reasons:

- The miner–processor would be less massive and complex and would not need its own power system.
- The miner–processor could be maneuvered more easily into irregular minable areas between craters and block fields.
- The inclusion of refining, habitat, control, and power systems in the central station may reduce the mass of payloads required for meeting initial production objectives.
- The need to have separate transport of volatile-filled tanks to a central refinery would be eliminated.

- Telerobotic operation of the miner may be more cost-effective and potentially may eliminate full-time crews on the miner–processor units, further simplifying those units and reducing personnel costs.
- Overall risk would be reduced through limiting exterior human activity to maintenance and possible temporary hands-on operation to continue production during maintenance and repair periods.

To make a final determination of the optimum technical and cost solution to the challenge of mining the regolith, a number of tradeoff studies will be required. These include comparison of the following options:

1. Spiral mining and processing by a mobile miner–processor outward from a central, periodically mobile station housing refining, power, control, and habitation functions.[6] A telescoping arm would transport extracted volatiles to the station and provide power and operations support to the miner–processor.

2. Rectilinear mining and processing by a mobile miner–processor, with self-contained power and control functions, along parallel mining paths within defined, rectangular mining blocks. Extracted volatiles stored temporarily in reusable pressure tanks prior to transport to a central refining facility.

3. Optimized balance in both (1) and (2) above, between human operators, telerobotic operation, and autonomous robotic operation. Tradeoff considerations would include, cost, complexity, reliability, and annual production rate.

7.2.2 Equipment design

The available information on resource concentration and the conclusion that possibly a third or more of that resource can be released by agitation establishes some initial constraints on regolith mining and processing (see Chapter 6). Figure 7.4 gives a diagrammatic representation of the flow paths of materials during regolith mining and processing. Similarly, Figure 7.5 provides the flow paths for the refining process. The following outline of some of the initial constraints represents only a first step in the design process:

1. Initial excavation at the start of miner–processor operations.
    (a) Excavation to 3-meter depth (consider designs and benching requirements that allow excavation to 6 meters based on measured depth of the local regolith).

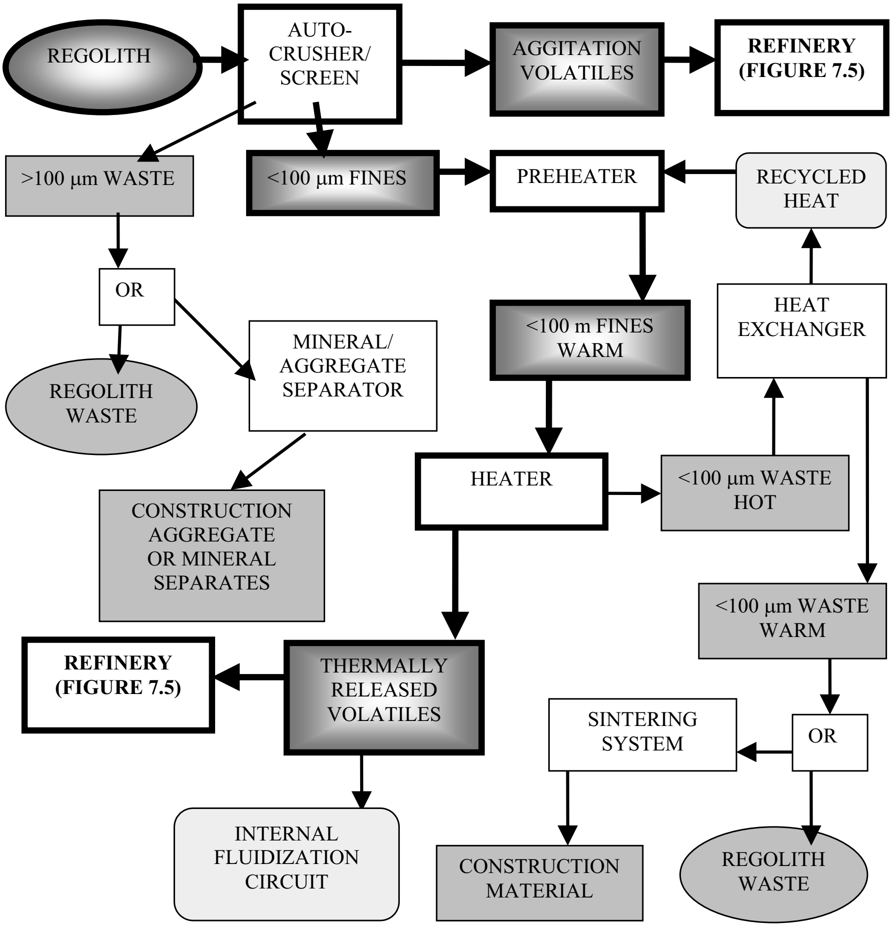

FIGURE 7.4 Lunar regolith mining–processing flow diagram for the recovery of solar wind volatiles.

   (b) capability of avoiding surface and buried boulders too large to process (boulder distribution provided by initial mine mapping and look-ahead radar or acoustic system).
   (c) Little or no losses of volatiles during initial agitation of excavated material prior to primary processing.
   (d) Efficient "dig in–dig out" capability to begin or terminate mining in a specific area.

2. Processing of regolith fines and breccia fragments.
   (a) Initial processing capable of recovering volatiles released by agitation.

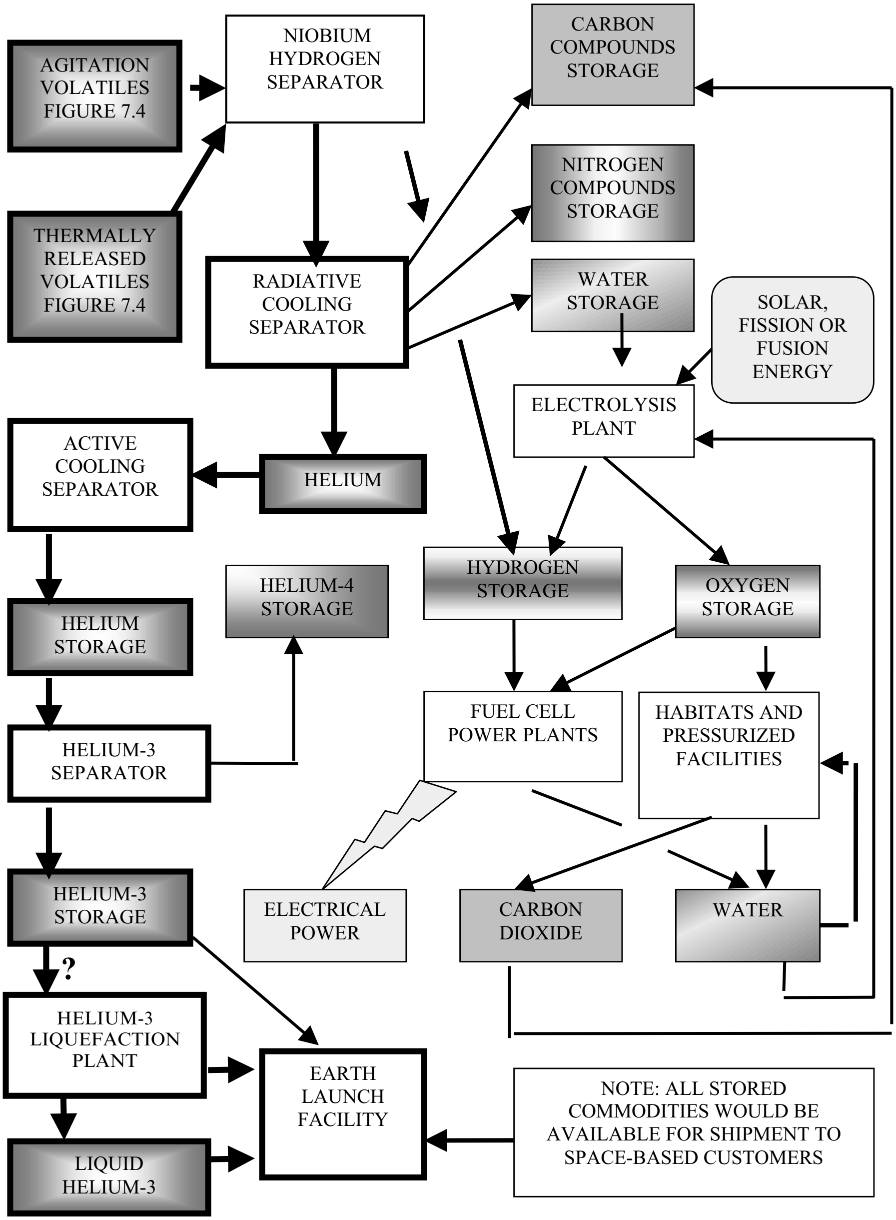

FIGURE 7.5 Solar wind volatiles refinery schematic flow diagram.

   (b) Agitation of fines and auto-crushing of agglutinates and regolith breccias (consider role of fluidization of fines and having hard rock, that is, basalt fragments acting as crushing elements as in terrestrial ball mills).
   (c) Recover volatiles released by agitation processing.
   (d) Transport volatiles separated by agitation to refining unit or interim storage.
   (e) Separation of fines $<100\ \mu m$ (mean size of <1 mm fraction of regolith is about 50 μm,[7] and a trade study should be made to determine the most cost-effective size cutoff).[8]
   (f) Rejection and off-loading of waste material $>100\ \mu m$ (consider option of sizing or processing waste to produce road and construction aggregate, glass for fiberglass[9] and solar cells, and iron for steel).
   (g) Transport of fines to secondary processing (consider fluidized transport).
3. Secondary processing of <100-μm fines
   (a) Preheat with recovered waste heat (consider moving hot, fluidized waste fines through heat exchanger prior to dumping overboard).
   (b) Heat to $\leqslant 700^\circ C$[10] (consider microwave,[11] solar thermal,[12] or fission heating) with real-time tuning available to maximize recovery.
   (c) Recover volatiles released by heat processing.
   (d) Transport volatiles to refining unit or to interim storage.
4. Refining
   (a) Hydrogen separated from hot volatiles by passage through heated niobium window.[13]
   (b) Cooling by radiation to space to sequentially liquefy water, carbon compounds, and nitrogen compounds.
      (1) Transport liquids to interim storage (consider buried inflatable bladders with either continuous radiative cooling or active cooling).
      (2) Separate water into oxygen and secondary hydrogen through electrolysis:
         - oxygen sent to habitats, fuel cells and storage;
         - secondary hydrogen sent to fuel cells and storage;
         - recycle waste water from fuel cell power plant back to oxygen and secondary hydrogen production plant (determine if recycling is cost-effective versus producing more primary oxygen and secondary hydrogen).
   (c) Transport cooled primary hydrogen–helium mixture to active separation plant:

        (1) transport liquefied hydrogen to storage (fuel for propulsion and fuel cells);
        (2) transport cold helium to helium-3 separation system.
    (d) Separate helium-3 from helium-4 gas (superleak membrane process[14]):
        (1) transport helium-4 to interim storage (for pressurization fluid and propulsion augmentation).
    (e) Actively liquefy helium-3 for shipment if trade study shows it to be cost-effective versus pressurized as cold gas with much larger volume.

5. General design philosophy for lunar surface equipment that is critical to both safety and the meeting of contracted production requirements.
    (a) Systems and components should fail to operate, fail to manual, fail to safe in that sequence.
    (b) Embedded and predictive diagnostics supported by lifetime component testing and operational verification.
    (c) Replacement of failed functions by "line replaceable unit" (LRU) with eventual lunar site repair of most LRUs.

A few detailed efforts to design a lunar regolith miner–processor have been undertaken.[15] That done by Sviatoslavsky of the University of Wisconsin's Fusion Technology Institute (Figure 7.1) illustrates many of the essential concepts that will be required of any regolith miner–processor. His Mark II Miner consists of a bucket wheel excavator on an arm that swings a 150-degree arc of excavation in front of the miner–processor. It basically "eats" its way through the lunar regolith in a temporary trench that is 3 meters deep and 11 meters wide. The mined material cascades backwards out of the bucket wheel trays onto a conveyer belt and then onto progressively smaller sieves with rejected material returned to the trench at the side of the miner–processor. In this design, fine particles less than 250 μm move into the pressurized interior of the miner–processor by way of two power screws (augers).

Inside the miner–processor, the regolith fines enter a stream of gas flowing at an optimized velocity so that particles less than 100 μm (about 50% of the total regolith) are fluidized and join the gas stream. Coarser particles again are ejected into the trench. A cyclone separator separates the fluidized fines from the gas, dumping them into hoppers that feed them trough a three-stage heat exchanger. These stages consist of a "preheater," a "main heater," and a "recouperator." The main heater sits between the preheater and the recouperator. Via heat pipes, the heat recovered by the recouperator transfers upward to the preheater. It is estimated that the main heater will only need to add about 15% of the total heat necessary to remove solar wind volatiles with a preheated temperature of 600°C and a maximum treatment temperature of ~700°C. Released volatiles move upward as the fines move downward through the heat exchanger, with a particle residence time in the heater of about 20 seconds. Volatiles are pumped into high-pressure cylinders mounted on the back of the miner–processor. As these cylinders fill, they are moved to a refinery located at a fixed base. The processed fines, about 100°C hotter than the ambient regolith temperature, are ejected from a "differentially pumped ejection chamber" to the rear of the miner–processor, completing the refilling of the trench. The general design parameters of the Mark II Miner are given in Table 7.1.

TABLE 7.1 Design parameters for the Mark II Miner

Parameter	Value
Annual collection rate of helium-3 at 10 ppb	33 kg
Mining hours per year	3942 hr/yr
Excavation rate	1258 tonne/hr
Depth of excavation	3 m
Forward speed of miner	23 m/hr
Area excavated per year	1 km^2/yr
Processing rate	556 tonne/hr
Lunar process energy (82 GJ/g with solar thermal energy)	12.3 MW
Heat recovery	85%
Estimated operating electric power	200 kW

The Mark II Miner represents an excellent place to start in the examination of how an operational miner–processor should be designed. Relative to that original design, however, the following additional factors should be considered with respect to their impact on design, mass, manufacturing, lunar surface assembly,[16] costs, and operations:

- Spiral versus rectilinear mining and processing strategy.
- Electrical power system (see Section 7.4).
- Heat exchanger technology advancements.[17]
- Regolith fines heating system (see Section 7.4).
- Effects of a range of physical (geotechnical) characteristics in the regolith:
  - specific gravity
  - proportion of fines
  - rock size-frequency distribution

  - proportion of indurated regolith fragments
  - concentration of iron sulfide
  - cohesiveness
  - abrasiveness
  - hydrogen effects (if any)
  - water and dissolved salts effects on processor
  - dust effects on everything (see Section 7.3).
- Crushing of indurated fines.
- Recovery of volatiles released by initial agitation and crushing.
- Large rock–rock field avoidance:
  - visual
  - radar
  - sonar.
- Large rock removal from mining path.
- Maintenance requirements:
  - pre-deployment lifetime tests
  - imbedded diagnostics
  - anticipatory component replacement
  - "fail to operate, fail to manual, fail to safe" design rule
  - refurbishment schedule.
- Duty cycle of equipment (continuous versus intermittent).
- Personnel work–rest–recreation cycle.
- Comparison against terrestrial mining–processing benchmarks.[18]
  - conceptual approaches to mining and processing bulk materials
  - low mass structural materials
  - manual vs automated vs remote control tradeoffs
  - mining rates as function of time
  - dust management
  - reliability
  - risk management
  - personnel attention, training, and safety
  - maintenance and refurbishment schedules.

Modeling that permits analysis of the interactions and sensitivities of the various technical and operational issues listed above will be helpful in required tradeoff studies as well as in estimating, monitoring and improving cost control.[19] General and specialized simulants of the lunar regolith will be important for acquiring the test data that will support miner–processor design.[20]

An initiative to recover lunar helium-3 will need to consider the environmental aspects its activities[21] both because it is appropriate and because it is an explicit requirement of controlling space law (see Chapter

12). Visual changes, atmospheric contamination, and waste disposal are the potential areas of environmental concern that would affect the Moon. Destruction of small, craters, those less than about 20 meters in diameter, and possible slight changes in the albedo (downsun or zerophase reflectivity) of the surface will be the primary visual effects. None of these changes, however, will be visible from Earth even with the best telescopes. Agitation of the regolith during mining and possible leakage during processing will release very small amounts of implanted solar wind volatiles into the local "atmosphere," but certainly less than is released daily by meteor impacts elsewhere on the Moon. These gases will be ionized rapidly and entrained by the solar wind and be lost to the Moon or reimplanted elsewhere with no long-term effect.[22] Dust activated by mining, of course, returns ballistically to the nearby surface due to the lack of significant atmosphere.

Solid "waste" will actually have significant value. That which constitutes hardware brought to the Moon or made there will be kept in inventory so that it can be refurbished or cannibalized depending on need. Solid, liquid, and gaseous human waste will be reprocessed for use in lunar agriculture. The lack of wind and water on the Moon, of course, insures that all waste will remain localized in repositories and cause no general contamination of the lunar environment.

The net environmental effect on the Earth–Moon environment will be hugely positive because of lunar helium-3 fusion power's reduction in terrestrial greenhouse and acid-forming gases, radioactive waste, and fossil fuel mining requirements.

There remains significant uncertainty in the analysis of production rates and mining–processing concepts. Reduction in this uncertainty will require the development of detailed knowledge of helium-3 distribution so that the best initial mine site can be selected and operational mine planning can be optimized toward minimum costs. Other factors being equal, a new mine always tries to begin with the highest known grade and lowest cost mining situation.[23] This gives the early cash flow needed to pay for the enterprise's infrastructure as soon as possible and to demonstrate to investors and bankers that the mine is a viable concern.

In addition to the regolith's titanium concentration and age as indicators of where to mine for helium-3, fresh blocky-rim impact craters large enough to penetrate the local regolith indicate where not to mine. If not avoided, such craters and their blocky ejecta, both on the surface and buried, would reduce the productivity of mining-processing machines designed to excavate primarily fine regolith material with high helium-3 concentrations. Many blocks near these craters will be too large for the miner–processor to handle. Surface block fields are visible and easily avoided. On the other hand, the location of buried block fields must be inferred by careful geological mapping of features that indicate the location of buried crater ejecta.

Micrometeor and small meteor impacts degrade surface boulders into regolith. After billions of years, crater age constitutes one major indicator of the presence and abundance of un-degraded blocks in an area to be mined. Major changes in crater morphology with time, based in part on my Apollo 17 observations, are as follows:

1. Category One: Youngest and statistically the smallest craters that are characterized by bright halos and irregular but coherent pools of impact glass on their floors and regolith breccia fragments scattered on their walls, rims, and ejecta blankets. Category One craters are probably less than one million years (m.y.) old.
2. Category Two: The crater's bright halo has faded but otherwise the same as Category One above. Category Two craters are probably 1.5–3.7 m.y. old.[24]
3. Category Three: Pools of impact glass on the crater floor have disappeared and regolith breccia fragments are degraded. Category Three craters are probably 2–5 m.y. old.[25]
4. Category Four: Visible regolith breccias are fully degraded. If the crater penetrated the regolith to bedrock, there will be visible bedrock fragments on their floors, walls (outcrop?), and as ejecta. Category Four craters are probably 10–20 m.y. old.[26]
5. Category Five: No blocks are visible on crater floors but are still present in walls (outcrop?) and as ejecta. Category Five craters are probably 20–100 m.y. old.[27]
6. Category Six: No blocks are visible except possibly locally in walls (outcrop?). They are >100 m.y. old.

Mapping crater characteristics and visible boulder distributions will provide general insights into a number of parameters that will affect mine planning. Recent digitization of Apollo Metric Camera photography[28] taken from lunar orbit, as well as other data from the Lunar Orbiter,[29] Clementine,[30] Lunar Prospector,[31] Smart[32] and Selene[33] missions, will assist greatly in this mapping. Craters of Category One to Four that penetrate the regolith and expose blocks of the underlying bedrock can be used to map variations in the depth of regolith. Bench craters, which have a continuous or partial bench in their walls, indicate a sharp increase in compaction or strength of the regolith with depth. Pit-bottomed craters appear to have responded to near surface reduction in compaction with depth. Craters of insufficient depth to penetrate the regolith to bedrock, but have basalt boulders in their ejecta blankets, indicate a concentration of buried boulders, presumably ejecta from an older crater.

The day-to-day avoidance of buried blocks, however, will require mining–processing machines to employ look-ahead technologies. These may include various electromagnetic sensing systems,[34] such as wave detection and imaging (EDIT), radio-imaging methods (RIM), and ground-penetrating radar (GPR). As the regolith, in contrast to fresh boulders, contains ubiquitous nanophase iron and no water, electromagnetic techniques should work well in identifying high-density (3.5 g/cm^3), low-nanophase iron blocks in the relatively low-density (1.7 g/cm^3), high-nanophase iron regolith. The density and seismic contrasts between regolith and blocks indicate that look-ahead acoustic/seismic scanners will be an alternative approach worthy of evaluation.[35]

In addition to block avoidance, day-to-day "tuning" of the miner–processor operation will probably require systematic, preprocessing characterization of the geotechnical properties of the regolith. Mapping of these properties can be performed remotely by sensors on automated rovers, data from which would be processed automatically and fed to the miner–processor computer as particular parameters changed in the regolith immediately ahead. Some properties of interest are the average and range of grain-sizes, granular flow characteristics,[36] proportion of agglutinate and regolith breccia, cohesiveness, helium and/or titanium content, and proportions of other solar volatiles. Along with mass spectrometer data on volatiles released during drilling, parameters from which geotechnical properties may be derived include bulk density and porosity, relative density, compressibility, shear strength, cohesion, friction angle, bearing capacity, slope stability, electrical conductivity and dielectric permittivity, angle of internal friction, and bearing strength.[37]

7.3 DUST: A SPECIAL PROBLEM

The invasive nature of lunar dust represents a more challenging engineering design issue, as well as a health issue for settlers (see Chapter 13), than does radiation.[38] With over half the mass of the regolith made up of abrasive particles less than 100 µm in diameter, this dust will penetrate into any space, fabric, bearing or moving parts not specifically sealed against it. Habitats and their internal systems will need to be designed either to tolerate dust or to prevent its intrusion, and to do either indefinitely. The first defense for all pressurized facilities will consist of a "dust lock" at all entrances that also will serve as a changing room and space suit cleaning and refurbishment area.

Our Apollo experience indicates that dust control can be carried out successfully on the Moon. The pressure suits and the interior of the Lunar Modules were exposed to dust and tolerated it without significant degradation in performance for over three days.[39] Suit glove and helmet bearings had circumferential scratches from dust, but showed no significant change in leak rates during pre-excursion tests. The lunar rovers, on the other hand, had their wheel bearings and electronics successfully sealed against any penetration by dust.

On the problem side of the Apollo experience, however, dust accumulated on mirrored and other thermal control surfaces and had to be removed frequently – but only partially successfully – to avoid excess heating. Some equipment did overheat.[40] Exposed connectors on various tools eventually jammed on the third day of use after repeated matings and dematings. Suit visors required to be cleaned between excursions to remove electrostatically adhering dust. Dust also prevented the knife-edge indium seals of any of the sample return containers (rock boxes) from maintaining a vacuum during storage in the spacecraft and during transit to the Lunar Receiving Laboratory.[41]

Dust will probably never be eliminated as an engineering and operational issue, and dust mitigation strategies will need to be innovative and continuously applied. Space suit design, if feasible, should include continuous rejection of dust from fabric, bearings and other working components.[42] Habitats and other pressurized facilities will require air locks also to be dust locks in which dust brought in from outside is contained and removed. The interior design of habitats must make for ease of cleaning or for automatic accumulation and elimination of dust that escapes from the dust lock. Interior equipment, like exterior equipment, should be designed to prevent the penetration of dust into sensitive electronic and mechanical components.

7.4 THERMAL AND ELECTRICAL POWER

Significant electrical and thermal energy will be required for mining, processing, and refining the lunar regolith as well as for the needs of the facilities and habitats constituting a lunar settlement. Four options exist for meeting these requirements.[43] They are: solar energy,[44] solar energy combined with lunar hydrogen and oxygen fuel cells, nuclear fission, and nuclear fusion. Figure 7.6 gives a schematic representation of the operational contrasts between these four options and helps to visualize the tradeoff studies necessary before a final, long-term power system can be chosen. In all options, the net benefit or cost from preheating the regolith fines using waste heat from prior processing will need to be evaluated, including the cost and complexity of incorporating heat exchangers in the process stream. The bottom line in these tradeoff studies will be end-to-end, relative capital and operational costs – costs that partially reflect the net energy conversion efficiency within each option.

An additional result of the tradeoff studies will be an evaluation of the efficiency and design complexity of thermal heating of the regolith fines by solar or nuclear thermal sources versus heating by microwaves. Microwave generation, of course, requires a source of electricity, adding losses during energy conversion. This loss to net conversion efficiency, however, may be offset by increased efficiency in heating due to efficient microwave coupling[45] with the finely distributed, nanophase iron particles in the regolith fines.[46]

7.4.1 Solar energy

Concentration of solar energy for direct heating of the regolith fines to extract solar wind volatiles and water has been assumed in most previous studies.[47] With the discovery that nanophase iron particles give highly efficient microwave coupling, an intermediate solar photovoltaic system to produce electricity would need to be evaluated as a suboption. This photovoltaic system would also need to be sized in order to provide for other electrical requirements.

7.4.2 Solar and lunar hydrogen–oxygen energy cycle

Once lunar hydrogen and oxygen are available, the option exists for using fuel cells for electricity production along with solar energy to regenerate hydrogen and oxygen from fuel-cell-produced water. The combined solar and lunar hydrogen–oxygen energy system could be jump-started with hydrogen and oxygen brought from Earth, pending the availability of sustaining lunar hydrogen and water (oxygen) production. This partially closed system could generate both microwaves and additional electricity for other needs. Of course, the electricity necessary to electrolyze fuel cell water, as well as for the initial production of lunar oxygen from lunar

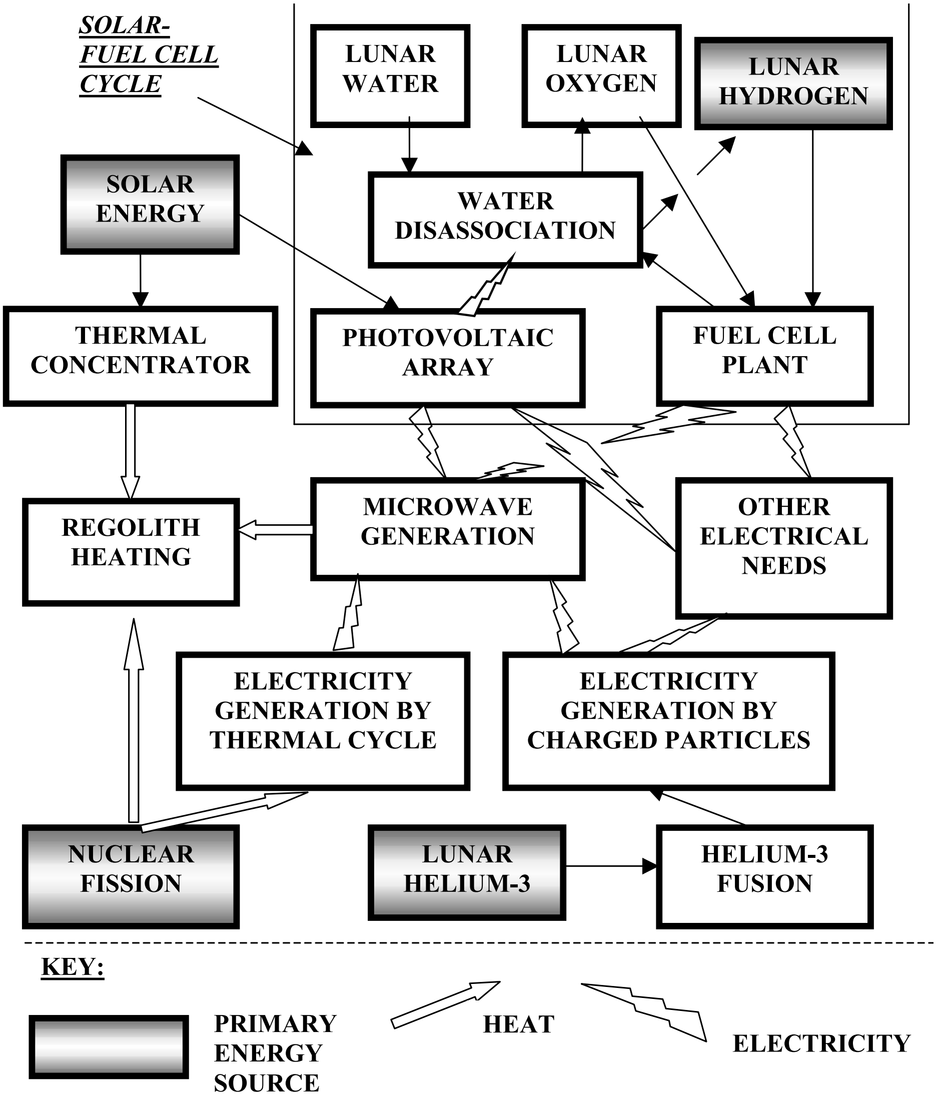

FIGURE 7.6 Schematic flow diagram illustrating options for producing thermal and electrical power for lunar operations.

water, could also be provided by nuclear fission or fusion sources, which are suboptions that should be evaluated.

7.4.3 Nuclear fission

Like solar energy, nuclear fission can provide both thermal and electrical energy for heating regolith fines either directly or through microwave energy. Other electrical requirements can also be met with this option. The main objection to nuclear fission systems in space will be the need to launch radioactive materials from Earth as fuel. On the other hand, many radioisotopic thermal electric generators (RTGs)[48] have been launched and the means of preventing dispersal of radioactive material in the event of a launch or entry accident are well known and tested. For example, Apollos 12–17 launched with plutonium fuel elements on board and the fuel element on Apollo 13's Lunar Module Aquarius re-entered the Earth's atmosphere and sank in the Pacific Ocean without adverse incident. A Saturn VI capability to *always* abort to orbit during launch would further reduce any risk.

7.4.4 Helium-3 fusion

Once relatively small helium-3 or deuterium–helium-3 fusion power plants have been developed they can be considered as power sources for lunar systems. Long-term supplies of helium-3 fuel will be available from lunar sources; however, if deuterium is required, it will need to be imported because the hydrogen to deuterium ratio in the lunar regolith[49] appears to be three orders of magnitude less than that found in terrestrial water, or about 10^{-7}. If water derived from comets becomes available from the lunar poles (the hydrogen/deuterium ratio in comets is about 3.2×10^{-4} versus 1.56×10^{-4} for terrestrial ocean water[50]), this would become an alternative, long-term source of deuterium on the Moon. Although some waste heat will be available, it is likely that microwave energy will be the primary means of heating regolith fines under the fusion option. Relative to other energy systems under consideration, the potential high efficiency of helium-3 fusion and overall plant simplicity may ultimately favor this option.

7.5 EXPORT TO EARTH AND SPACE

Exporting lunar helium-3 to Earth and its by-product resources to elsewhere in space constitutes a relatively small challenge compared to the development of commercial fusion power plants, heavy lift boosters, and a lunar mining and processing capability. Each shipment of helium-3 would probably be 100 kg or less in mass in order to manage the risk of losing it, but the optimum shipment mass will be determined by consideration of shipment value, insurance costs, risk assessment, shipment costs versus shipment mass, and customer inventory requirements. (100 kg of helium-3 has an estimated current energy equivalent value of about $140 million relative to steam coal, as discussed in Section 6.3.)

As indicated in the flow diagram of Figure 7.5, the refined helium-3 will be either in the form of a pressurized gas or a cryogenic liquid near absolute zero in temperature. Owing to its larger volume, gaseous helium-3 will require a larger shipping spacecraft than will the same mass of liquid. The liquefaction of helium-3 and its maintenance at extremely low temperature, however, would add costs for production as well as those due to greater spacecraft complexity. Such added costs may outweigh the costs of accommodating the larger volume of pressurized gas. At this time, in the absence of a specific tradeoff study, it would appear that shipping helium-3 as a gas may be the preferable business choice.

The launch of each shipment from the Moon, as small, unmanned spacecraft, may be provided by one of several options, the choice of which would also require a cost tradeoff study. Rocket booster options include those fueled by hydrogen and oxygen, methane[51] and oxygen, or several possible metal and oxygen bipropellant systems,[52] all lunar derived. Electromagnetic launch powered by the settlement's base load power system would be another possibility. The terrestrial export spacecraft's launch trajectory would be designed so that recovery would be at secure locations on Earth, but would need to have a guided entry into and through the Earth's atmosphere in order to accomplish a pin-point landing. Helicopter recovery, while the helium-3 shipment container is still airborne, or a guided Para Foil recovery into a guarded area, might accomplish such a precise landing.[53] Transport of the helium-3 to a specific customer would follow.

Shipments of lunar hydrogen, oxygen, water, and other resources to customers in Earth orbit or elsewhere in space will require more sophisticated spacecraft. Earth-orbit customers will require the shipment to be aero-captured in the atmosphere and then guided to a rendezvous with the purchaser's space station or other spacecraft. Customers in transit to Mars may need to pick up their consumables at an Earth–Moon libration point[54] depot near the Moon.

7.6 RISK MANAGEMENT

Risk management in the context of a return to the Moon involves those plans, designs and activities that will eliminate or minimize the effects of identifiable risks to both investors and employees. It will range from the management of finances and business practices, to the design of rockets and spacecraft,[55] to the conduct of lunar operations, and the delivery of resources to customers. It will encompass, among many other things, rules for conducting flight operations, management of a steady improvement in productivity, and the management of costs and debt servicing.

Both familiar and unfamiliar challenges will be posed by risk management for a "Return to the Moon" enterprise. For example, the design of a new Saturn VI booster should be undertaken with the requirement that once launches to the Moon are recommenced, there can be no extended "stand-downs" to redesign the booster in the face of a significant problem or accident. This requirement is in contrast to NASA's history of long delays in restarting flight operations in the face of its three worst accidents – the 1967 Apollo 204 fire, the 1986 *Challenger* explosion, and the 2003 *Columbia* break-up on entry (see Section 9.2.2).

The 14-month delay after the Apollo 204 fire is understandable as it occurred during the development and test flight period and the Apollo spacecraft involved had never flown in space as a manned craft. However, owing to an unforgivable neglect of the hazard of fire in a spacecraft, the delay actually resulted in a vastly improved Block II spacecraft[56] (already under development at the time of the fire) and contributed to an eventual acceleration of the Apollo schedule. On the other hand, delays of 32 and at least 29 months in the return to flight after the *Challenger* and *Columbia* orbiter accidents, respectively, came from an inherent lack of confidence in the Space Shuttle design. This lack of confidence followed as a direct result of the under-funding of the early Space Shuttle design and development program and the necessary high-risk compromises that were made to stay within the funding limitations. Service in the United States Senate during this period allowed me to witness this irresponsible Congressional and Administrative behavior first hand.

Delays as long as those for *Challenger* and *Columbia* could not be tolerated either financially or operationally during the activation and start-up production phases of a private sector financed "Return to the Moon." Eliminating the possibility of a major accident is clearly the most cost-effective, long-term way to manage financial as well as human risk. As an example, the design, development, and test effort for the new Saturn VI booster must be funded and implemented in such a manner as to eliminate operational risk in every way possible. It must also create a level of confidence such that flights can resume quickly, once the cause of a major problem, if any appears, has been identified. "Robustness" will be the watchword for this booster. As with the Saturn V of Apollo, the new booster must be robust and forgiving enough to avoid major problems and allow an abort to a safe orbit so that crews are not endangered and equipment can be recovered and relaunched from Earth orbit to the Moon. This implies that the new booster should be designed with multiple liquid-fueled rocket engines and with thrust margins necessary to overcome the significantly reduced capability that would come from failure of one engine at any time during the boost sequence.

As with Apollo, the twin issues of crew safety and crew rescue, philosophically, are probably addressed best by designing and manufacturing quality equipment rather than by plans to have rescue boosters and spacecraft on call. Tying a launch, or the continuation of an operational mission to the availability and readiness of a second booster and spacecraft, constitutes a costly and overly constraining requirement and inherently increases the overall risk to the success of the mission. Two boosters have to work instead of only one. A back-up booster implies less than adequate levels of confidence in the primary systems. It should be noted that, in the situation where all lunar personnel become settlers upon arrival on the Moon, the question of rescue from that location disappears. Only the easier requirement for resupply remains. Ultimately, as lunar scientific expeditions and lunar tourism become feasible, Earth-return vehicles will be required and aerobraking, hypersonic and subsonic energy management, and Earth-landing issues of technology and risk, will need to be addressed.

The new Saturn VI heavy lift booster, as well as equipment necessary to work and live on the Moon and to provide essential support functions on Earth, must also be designed to minimize both the possibility of catastrophic failure and the possibility of unplanned reductions in production. That requires materials, components, parts, subsystems and systems to be selected, designed and manufactured to the specification that the total system will "fail gracefully." One way to constrain designs to ensure that failure is "graceful" is to require that critical units "fail to operate, then fail to manual, then fail to safe." "Fail to operate" implies that each critical unit has a "redundant" unit to take over automatically in case of failure. Particularly critical units, such as those that relate to operator safety, may need to be triply redundant. "Fail to manual" means that if all redundant units fail, an operator can continue to use the total system manually until a non-disruptive replacement of a failed unit can be accomplished. “Fail to safe” provides the final protection by insuring that other portions of the total system are not damaged if both normal and manual modes of operation fail.

In addition to quality design and manufacture, the most cost-effective way to avoid disruptive equipment failures is through well-planned and well-executed preventive maintenance. Such maintenance requires that units potentially subject to age-related failures have the test data necessary to schedule preventive replacement or to calibrate embedded diagnostic sensors. The engineering philosophy should be one of designing, manufacturing and maintaining for *indefinite* operational life rather than for some arbitrary “mission” life after which the equipment would be discarded. In this context, designers should always anticipate that electronic and dynamic components, and possibly some structural components, would be upgraded as operational history is recorded and technology advances.

7.7 EMPLOYEE SELECTION AND TRAINING

Selection, training, and support of employees who will ultimately work and settle on the Moon – as well as those working in research, development, and operational activities on Earth – will be a critical and continuing task for any “Return to the Moon” initiative. Recent experience in teaching and working with young engineers, scientists and skilled workers supports that a large, highly motivated reservoir of potential employees exists in the United States. Many from other nations would also seek to join in an effort to “Return to the Moon.” Criteria for selection and training of employees will be finalized in concert with the development of engineering designs and operational plans. Because of cost considerations, one important selection criterion will be employee commitment to settle permanently on the Moon, not unlike the personal commitment made by the first settlers of new lands throughout human history. Lunar-based employees must accept contractually that all medical, social, and recreational requirements will be served on the Moon, with returns to Earth prohibited by cost considerations until regular round trip flights to Earth, including the possibility of vacations, have become a viable business.

Apollo taught us that the average age of employees should remain near 25 in order to tap the imagination, motivation, and stamina necessary to accomplish great and complex endeavors. Mid-level managers would be selected on the basis of previous experience and performance and their demonstrated ability to lead and motivate younger men and women. They largely should be between the ages of 30 and 40. Senior managers would be selected on the basis of technical and operational wisdom and demonstrated managerial performance. The age ranges suggested above, of course, are approximate and specific individuals should be evaluated on the basis of specific circumstances.

All new hires for jobs in research and development, as well as lunar and terrestrial operations, must have strong records in undergraduate or graduate studies from reputable engineering schools and departments. A core of young engineering research personnel with PhDs, or significant pertinent experience, must also be maintained with ages between 25 and 40. Based on previous experience with human capabilities to work in intense, highly charged environments, it is expected that the average period for peak performance in one concentrated area of effort will be about 10 years. Therefore, employee contracts must recognize that the enterprise will continuously "graduate" employees who have not been singled out for advancement. As long as the enterprise is growing, the potential for advancement will be indefinite, with many new employment opportunities created over time. Movement of relatively older employees out of "Return to the Moon" units into less intense activities will, however, always be necessary to make room for new staff and to stay within the desired limits on average age in the priority workforce. Depending on need and skills, these graduates would be placed in other job areas either within the larger corporate structure or outside that structure through active relocation assistance. These forced job changes serve two other purposes. For the individual, the change offers the opportunity for professional rejuvenation. For families, the change may relieve some of the stresses that can be generated by intense dedication to a particular job.

Selection criteria for employment in the cadre of lunar production and settlement personnel will be more complex than those associated with terrestrial design, development, and support. In the early years, it is expected that this group will be between 30 and 40 years in age at the time they reach the Moon. They will tend to be older with more demonstrated experience and maturity in their required fields versus their age peers in the terrestrial units. Because of the contractual commitment to settle permanently on the Moon, couples who both meet the selection criteria and demonstrate a strong personal relationship, will have selection priority. All in the lunar cadre must have a broad breadth of training and experience in two or more relevant fields, or have demonstrated an aptitude and a motivation to diversify their expertise into other required specialties (see Section 7.10). All employees who are not initially part of the more experienced and mature lunar production and settlement cadre should be made aware of paths of professional development that might lead to later assignments to that cadre.

Employee training will be a critical function in all aspects of booster, flight, and lunar surface operations. The Apollo and Space Shuttle experience will be extraordinarily relevant to the organization of this training.[57] As lunar settlement operations become mature, training activities of specific relevance to safe and efficient operations at the settlement will increasingly be conducted on the Moon. Training for proficiency and advancement among settlers will combine on-site and distant learning techniques.

7.8 EMPLOYEE COMPENSATION

A private sector lunar enterprise will use standard approaches to compensating employees, although some special considerations will be required. In addition to salaries, compensation can include bonus plans, incentive stock, deferred salary payments, and paid vacation flights to Earth or the Moon after regular tourist flights become available. The prime motivating compensations for the foreseeable future, however, are expected to be participation in an endeavor that places human beings permanently on the Moon and provides the Earth with an alternative to fossil fuels for the production of electricity.

7.9 IMPORTED CONSUMABLES AND OTHER SUPPORT

Lunar oxygen and water should be available soon after helium-3 production commences. Food production will probably begin within two years. Until production of the consumables necessary to support lunar operations, however, those materials will need to be imported from Earth. Additionally, parts will probably need to be imported for equipment repair and refurbishment that are outside anticipated needs during the early shakeout of new production units and other facilities. It may also be necessary to add personnel from time to time as service requirements mature and expand. These early needs for imports are included in the cost analysis given below, but they are expected to become minimal within a few years.

7.10 PRODUCTION ECONOMICS

Estimates of annual recurring costs per 100 kg of helium-3 require assumptions related to a variety of parameters. These include costs of development and operating capital, the numbers of direct and support personnel, quantities of imported support materials and consumables, necessary Earth-based operational support, and required fees, insurance, and other direct costs related to lunar resource production and settlement activation. Consideration of a straw man production activation scenario can assist an understanding of these requirements. Such an activation scenario, given in Tables 7.2–7.5, is based on the payload capabilities of a new, 100-tonne lunar payload, Saturn VI booster discussed in Chapter 4. Primarily, for illustration purposes, this scenario further assumes the general requirements to implement the spiral mining concept for mining and processing discussed in Section 7.2 and shown in Figure 7.2. The principal payloads for the first unmanned landing consists of the Mobile Central Station (includes habitat for production personnel), the first miner–processor, and the telescoping control-transfer arm to connect the two. An automated system for offloading the station and the miner–processor from the landing module would be included, but the design would provide for a manual backup for offloading that could be employed, if necessary, by the first landed personnel.

The first manned landing would bring eight settlers having the primary skills indicated in Table 7.2. Their activation duties are given in Table 7.3. These eight first settlers, divided into two teams, would be responsible for bringing the first helium-3 production capability on line. Their landing module would serve as the initial habitat, pending activation of the central station's habitat section. Landing modules would be designed for later integration into the permanent base as private quarters and consumables storage units or possibly refurbished and reused as Moon-to-space ascent vehicles. The second unmanned landing of base equipment and the second manned landing of an additional eight settlers (see Tables 7.4 and 7.5) would establish the first permanent base. Depending on the rate of increase in orders for lunar helium-3, pairs of production activation landings could be substituted for the base activation landings for about a year or so.

TABLE 7.2 Straw man activation scenario for the first two booster manifests. Materials and personnel required to activate and operate a lunar helium-3 resource production settlement

Saturn unmanned launch–1U	Saturn manned launch–1M
• Mobile central station 1 - Power module - Habitation for 8 • Operations support - Volatile refinery - Rad-shield envelope - Cryogenic storage - Mobility system • Miner–processor 1 • Control-transfer arm • Multipurpose rover 1 – Team A - Aggregate separator - Regolith impeller - Earth mover - EVA consumables - Resource mapping - Remote rad-shield • Offloading system • Consumables - Power start-up	• Settler landing module-A (initial habitation) - 2 Engineers/operators for miner–processor 1 (backup for volatile refinery) – **Team A** - 2 Engineers/operators for volatile refinery (backup for miner–processor) – **Team B** - 1 Geologist/mine planner (deputy operations director) – **Team A** - 1 Operations support engineer (backup physician) – **Team B** - 1 Operations support/physician/engineer – **Team A** • 1 Operations director (backup geologist/mine planner) – **Teams A & B** • Multipurpose rover 2 – **Team B** • Offloading system • Consumables module - Food and water - Hydrogen - Oxygen

7.10.1 Non-recurring costs for initiating helium-3 production

Non-recurring, start-up capital costs for a private lunar resource initiative promise to be significant in addition to those associated with the new Saturn VI booster system and helium-3 fusion power plants discussed in Chapters 4 and 5, respectively. The initial objective of the first lunar resource production will be to produce 100 kg of helium-3 per year for the first 1000-MW, deuterium–helium-3 fusion power plant on Earth. (The actual requirement for a plant of this power capacity is about 75 kg/yr; however, a target production rate of 100 kg/yr will provide flexibility in contract risk management and in marketing.) The initial, primary operating objective of the first two lunar landings, supported by the third and fourth landing related to settlement activation, is the production of 100 kg of helium-3 within one year of the last of those four landings. The

TABLE 7.3 Initial major objectives for the crews of the first man landing in the straw man activation scenario (Table 7.2)

Activation Team B	Activation Team A
• Activate multipurpose rover 1 • Fill station radiation shield envelope with regolith • Activations - Power module - Habitation module - Control module - Cryogenic storage - Mobility system • Verify resource grade at mine site 1 • Move station to mine site 1 • Test and calibrate volatiles refinery • Initiate volatiles refining	• Activations - Miner–processor 1 - Multipurpose rover 2 • Move miner–processor and control-transfer arm to mine site 1 • Imbed miner–processor • Connect control-transfer arm • Test and calibrate miner–processor • Initiate volatiles production

TABLE 7.4 Straw man activation scenario for the third and fourth booster manifests. Materials and personnel required to activate and operate a lunar settlement supporting resource production

Saturn unmanned launch–2U	Saturn manned launch–2M
• Mobile crane/carrier • Main base infrastructure components • Agricultural production components • Multipurpose rover 3 • Regolith volatiles and water storage systems • Lunar oxygen production system • Base power system • Offloading system • Consumables module - Food and water - Hydrogen - Oxygen	• Settler landing module 2 (backup habitation) - 2 Engineer/operators for main base - 2 Engineer/operators for farm - 1 Geologist (exploration)/mining engineer - 1 Agricultural engineer/operations supervisor - 1 Physician/agricultural scientist - 1 Settlement manager • Consumables module - Food and water - Hydrogen - Oxygen

TABLE 7.5 Initial major objectives for the crews of the second man landing in the straw man activation scenario (Table 7.4)

Third activation crew (3M)
• Move main base components to planned locations – Construct regolith radiation shields • Integrate landing modules (1M and 2M) into main base infrastructure – Construct regolith radiation shields • Mothball four lander propulsion modules – Enable use of tanks for initial hydrogen and oxygen storage • Activate agricultural production facility – Fill regolith radiation shield envelope

cost of the first two landings would be directly allocated to initiation of this production capability. It also represents the maximum capital cost of adding additional capacity of 100 kg helium-3 per year, as payloads and personnel requirements may be less for new production capacity after the first unit is operational. The cost of the third and fourth landings to establish a permanent settlement would be allocated over many production units and, for the sake of this analysis, that cost is spread over the first 15 such units. Table 7.6 summarizes the estimated annual costs of capital attributable to each production unit. Based on the Section 4.2.2 analysis of the cost per launch for a new Saturn VI booster system, the two initial launches, at a five-per-year launch rate, would constitute a non-recurring capital cost of about $1 billion. Financing this capital investment at a 10% long-term rate will result in a recurring cost of about $100 million per production unit. The launch cost is shown as slightly less in Table 7.6 because of the allocation of recurring costs of consumables to operations (see Table 7.7)

Definition of the architectural and engineering design parameters for the lunar base and for mining and processing facilities will build on existing space and terrestrial experience. The primary business imperatives differing to various degrees from past experience in space are related to:

- minimum cost and maximum reliability;
- dealing permanently with lunar dust and radiation environments;
- indefinite life for lunar facilities and equipment;
- minimum feasible Earth-to-Moon launch mass requirements;
- maximum use of robotic and telerobotic systems and embedded diagnostics[58];
- support of ancillary activities such as research and tourism;

- minimum operational interaction with personnel on Earth;
- support of permanent settlement.

TABLE 7.6 Estimated helium-3 production related cost of capital components of a privately financed lunar helium-3 fusion power initiative (in $ millions)

Financial component	Capital	Cost long-term capital at 20%	Cost short-term capital at 10%	Total
Helium-3 lunar facilities/ production/export R&D	500 est.			
– Cost of capital		100		
Each miner–processor, etc.	100 est.			
– Cost of capital			10	
Each miner-processor/support delivery (two 100-tonne launches)(1)	980(1)			
– Cost of capital			98	
– Cost of capital (5th)			99	
Cost/miner–processor (1st)				208/yr
Cost/miner–processor (5th)				129/yr
Cost/miner–processor (15th)				116/yr
Settlement activation launches (two 100-tonne launches)(2)	1000(3)			
– Cost of capital (1/15th share)		13		
Cost of capital/100 kg (1st)				**221/yr**
Cost of capital/100 kg (5th)				**142/yr**
Cost of capital/100 kg (15th)				**129/yr**
Helium-3 coal equivalent value/100 kg (coal at $2.50/million BTU)				**140**

Notes:

(1) Through delivery of the fourth miner–processor, $20 million has been allocated to annual imports in consumables support for each production unit operating on the Moon (see Section 7.9.1). This drops to $5 million thereafter.

(2) Early launches and payloads are assumed to be self-insured until affordable insurance rates can be negotiated.

(3) Includes cost of lunar settlement facilities.

TABLE 7.7 Estimated annual recurring, operational cost components of a privately financed lunar helium-3 fusion power initiative (in $ millions per year)

Financial component	Capital	Cost of sales	Long-term at 20%	Short-term at 10%	Total
Operational costs/100 kg (1st)					**19.3**
Direct lunar personnel (six at $500K/person)		3			
Support/management lunar personnel (six) (two at $750K/person)		1.5			
Imported support $20M (∼7 tonne/yr)	20			2	
Earth support (20 at $500K/person)		10			
Fees, insurance, etc. ($100K/person)		2.8			
Operational costs/100 kg (5th)					**13.6**
Direct personnel (six at $500/person)		3			
Support/management personnel (two at $750/person plus 1/5th of eight at $550K/person)		2.4			
Imported consumables (∼1.5 tonne/yr)		5			
Earth support (1/5th of 20) ($500K/person)		2			
Fees, insurance, etc. (eight at $100K/person plus 1/5th of 20 at $100K/person)		1.2			
Operational costs/100 kg (15th)					**11.5**
Direct personnel (six at $500K/person)	3				
Support/management personnel (two at $750/person plus 1/15th of eight at $550K/person)		1.8			
Imported consumables (∼1.5 tonne/yr)		5			
Earth support (1/15th of 20)		0.7			
Fees, insurance, etc. (eight at $100K/person plus 1/15th of 20 at $100K/person)		1			

Design deviations from terrestrial mining experience will be in the areas of:

- integration of optimum human and robotic functions to minimize the number of workers;
- minimizing support costs;

- minimizing equipment mass; and
- flexible production expansion based on market demand.

Although it is estimated that each 100 kg of helium-3 will require the processing of about 2 square kilometers of lunar regolith to a depth of 3 meters each year (Section 6.3.2), such bulk tonnage mining and processing is well within the practical experience of mining and agricultural activities on Earth. Costs for developing a commercial lunar miner–processor and associated facilities, to be manufactured under long-term production contracts, would probably be in the range of $500 million, requiring about $100 million annually as the cost of long-term capital. Additional development costs may be financed as part of the development of fusion power technology if this estimate proves optimistic.

Development costs related to lunar helium-3 production would depend on the following:

- degree to which existing large tonnage mining and processing can be re-engineered for lunar applications;
- level of new design engineering required for the processing of lunar volatiles;
- adaptability of proven space habitat designs to lunar applications;
- complexity of Moon-to-Earth launch systems; and
- complexity of other required lunar surface support hardware and software.

Once hardware production commences, annual costs of capital for the first lunar miner–processor and associated facilities, providing a 100 kg/yr production capacity, are estimated to be about $221 million (Table 7.6). As listed in Table 7.6, this is made up of **$100** million as the cost of capital for development financing, **$10** million financing costs on $100 million for hardware, **$98** million financing costs on $980 million for launches to the Moon, and **$13** million as a 1/15th share in the activation of a lunar settlement. (It is assumed that $1 billion for the two new Saturn boosters necessary to activate the lunar settlement prior to initiation of resource recovery operations will be amortized over the first 15 miner–processors or in about 10 years.) The annual costs of capital would drop to about $142 million if five miner–processors were in operation and sharing the cost of development financing, and to $129 million if 15 units were in operation. The total cost of each launch and payload will probably be self-insured until demonstrated reliability allows affordable insurance rates to be negotiated.

TABLE 7.8 Estimated total non-recurring cost components of a privately financed lunar helium-3 fusion power initiative (in $ millions)

Financial component	Total (per yr)
Cost of capital/100 kg (1st)	221/yr
Cost of capital/100 kg (5th)	142/yr
Cost of capital/100 kg (15th)	129/yr
Operational costs/100 kg (1st)	19.3
Operational costs/100 kg (5th)	13.6
Operational costs/100 kg (15th)	11.5
Total Annual Costs/100 kg (1st)	**240**
Total Annual Costs/100 kg (5th)	**156**
Total Annual Costs/100 kg (15th)	**141**
Helium-3 coal equivalent value/100 kg	**140**

Recurring costs of capital for each helium-3 production unit also will include the cost to finance each unit, basically the hardware launched on the first unmanned booster (1U in Table 7.2). Cost of each production unit is assumed to be about $100 million, financed at 10% for an annual cost of $10 million. (Costs for the settler landing modules and related equipment on the first manned launch (1M) have been considered as part of the booster costs in the Chapter 4 analysis.)

It is likely that for at least the first five years after production activation, the provision of necessary new inventory and personnel in support of established lunar production capability could be made in connection with the addition of new production capacity. The frequency of lunar resupply, and thus these recurring costs (Table 7.7), will depend on the rate of growth in demand for lunar resources, the level of use of lunar resources at the settlement, and demand for ancillary use of the settlement's facilities for science, tourism, and other activities. Therefore, for the purpose of this general analysis, recurring payload requirements related to production capacity are assumed to be about 7000 kg/yr for each installed miner–processor (eight persons each) or about 7% of the Saturn VI booster system launch payload. The cost for this support of about $20 million per year per installed miner–processor is allocated here as a recurring cost rather than a non-recurring cost. This assumption is based on an estimate of about 700 kg of consumable support required each year for each lunar settler[59] plus about 1500 kg of miscellaneous supplies. After the fifth miner–processor is in operation, it is assumed that production of most consumables will be at the settlement, but there will be a continuing requirement for supporting imports of about 1500 kg/yr or \$5 million in recurring costs per production unit (Table 7.6).

Personnel costs (Table 7.6) introduce an additional annual recurring cost of production. They would include those associated with lunar operations as well as those on Earth in direct support of those operations. Including all personnel, annual recurring costs for the first miner–processor are about \$240 million. After 15 miner–processors are in operation on the Moon, each sharing the costs of production start-up capital, the annual recurring costs per production unit would drop to about \$141 million per 100 kg helium-3 per year or essentially breakeven with the assumed value of helium-3 on Earth (Section 6.3.1). Careful engineering design, operational planning, and financial management can probably reduce these costs. Further, net revenues would be enhanced by increases in the cost of industrial coal, the principal competitor for helium-3 in the 2010–2020 time frame.

7.10.2 Summary

The above estimates of the recurring costs for helium-3 production units suggest that those costs would approach breakeven relative to steam coal at \$2.50/million BTU after 10 to 15 production units have been placed on the Moon. Clearly, many opportunities exist to reduce production costs. Alternatively, many current unknowns could increase those costs. The next step will be to mature hardware designs to the point where more certain costs can be determined.

The energy exploration industry often refers to the cost of developing access to a resource as the "finding cost." For crude oil, finding costs are normally around \$1.00 per barrel, and for natural gas these costs are about \$3.50 per million cubic feet. Using 5.9×10^6 BTU as the energy content of a barrel of oil[60] and 5.6×10^{13} BTU (see Section 5.2.3) as the energy content of 100 kg of helium-3 fused with deuterium, the finding cost leading to helium-3 production can be calculated by assuming the following:

- The first resource "field" is 10,000 km^2 in area[61] and to a depth of 3 meters contains about 5000 100-kg units of helium-3 or the energy equivalent of 4.8×10^{10} barrels of oil.
- The capital and operational costs necessary to initiate production from this "field" are estimated in this book to be about \$15 billion.

These assumptions give a finding cost of about \$1.60 per barrel of oil equivalent for this size helium-3 field or nearly competitive with the average for oil finding. Of course, the actual finding cost for helium-3 would be much lower as the resource field in Mare Tranquillitatis is significantly larger than 10,000 km^2 in area – and is estimated to be about 84,000 km^2 for only the region of highest helium-3 concentration (see Section 6.3).

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61. A 10,000 km^2 area is chosen somewhat arbitrarily as an amount of measured resources (see Section 6.3.1) that clearly would be of interest commercially if fusion power customers existed on Earth. It also is consistent with the claim area suggested for an international regime of private property in Section 12.7.

8

APPROACHES: ORGANIZATIONAL OPTIONS FOR A RETURN

8.1 INTRODUCTION

MANY financial and managerial approaches exist that, hypothetically, could take us back to the Moon and access its resources as well as develop a terrestrial fusion power system dependent on one of those resources, namely helium-3 (see Figure 8.1). In order to examine the relative feasibility and cost of various approaches, each possibility must be evaluated against a reasonable spectrum of alternatives (see Figure 8.2). The six alternatives evaluated semi-quantitatively in this chapter include all-United States government, all international, and all-private approaches and combinations of these three. The six approaches chosen are defined as follows:

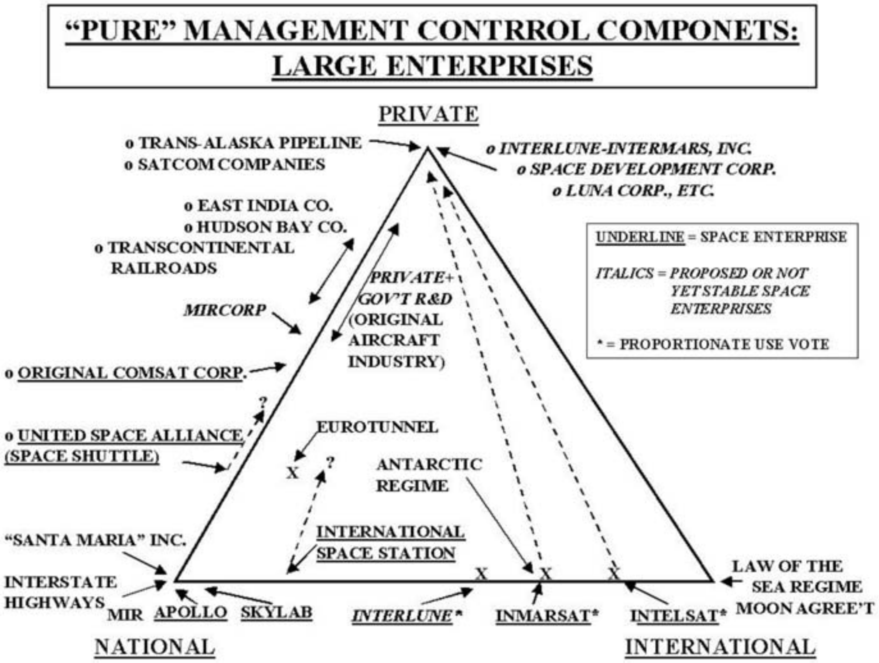

FIGURE 8.1 Graphical representation of various historical, current and proposed approaches to managing large projects relative to their incorporation of private, national and international components of management and finance.

1. *All-United States government.*[1] – This approach would be similar to that followed with the Apollo Program (see Chapter 9) and many other major national initiatives from world wars to the construction of the Panama Canal. The main difference between a modern, all-United States government initiative and Apollo presumably would be a significantly lower level of national urgency than that which sustained Apollo during the Cold War, although a major move by China, Russia, or others might change the current situation significantly. Otherwise, less urgency would be counterbalanced to some degree by a much clearer technical path to success based on the Apollo experience and more recent technical advances.

   With reference to a single government initiatives in 2004 and 2005, China has announced interest in prospecting for lunar helium-3 and the lunar science programs of Europe, India, and Japan have become increasingly active.
2. *Multilateral model, led by the United States government.*[2] The current agreements and management system set up for the International Space

MANAGEMENT CONTROL APPROACHES

APPROACH	EXAMPLE
• ALL U.S. GOVERNMENT	• APOLLO / PANAMA CANAL/ MANHATTAN PROJECT
• INTERNATIONAL, ONE NATION / ONE VOTE	• UN AGENCIES / LAW OF THE SEA REGIME
• MULTILATERAL CONSENSUS MODEL	• INTERNATIONAL SPACE STATION / ANTARCTIC REGIME
• MULTILATERAL PROPORTIONATE USE VOTING	• INTELSAT / INMARSAT
• PRIVATE / GOVERNMENT PARTNERSHIP	• MODERN AIRLINE INDUSTRY / U.S. AGRICULTURE
• PRIVATE + GOVERNMENT R&D	• PRE-1958 AIRCRAFT INDUSTRY
• ALL PRIVATE	• TRANS-ALASKA PIPELINE

FIGURE 8.2 Possible management control approaches for the development of lunar helium-3 fusion power.

Station (ISS) form a framework for this approach. Presumably, some lessons from the ISS experience would enhance its application to a new initiative, particularly if partners agreed to the United States as the lead decision-maker; however, having other countries in the critical path to success seriously delayed and raised the cost of the ISS.

Any future European initiative presumably would be undertaken under this model with French leadership, as would any Chinese-led Asian effort.

3. *Intelsat model.*[3] Studies of Intelsat (Figure 8.3) and Inmarsat – that is, user-based financial and management systems – strongly suggest that their approach should be examined closely. On the other hand, a one nation, one vote, United Nations style organization has not been included in this analysis because it seems very unlikely to be workable even though such an organization is envisioned by the 1979 Moon Agreement (see Section 12.4.2). The inevitable politicization of decision-making in such organizations, and the stagnation which invariably results, argues against its inclusion as being unsuitable for complex technical endeavors.

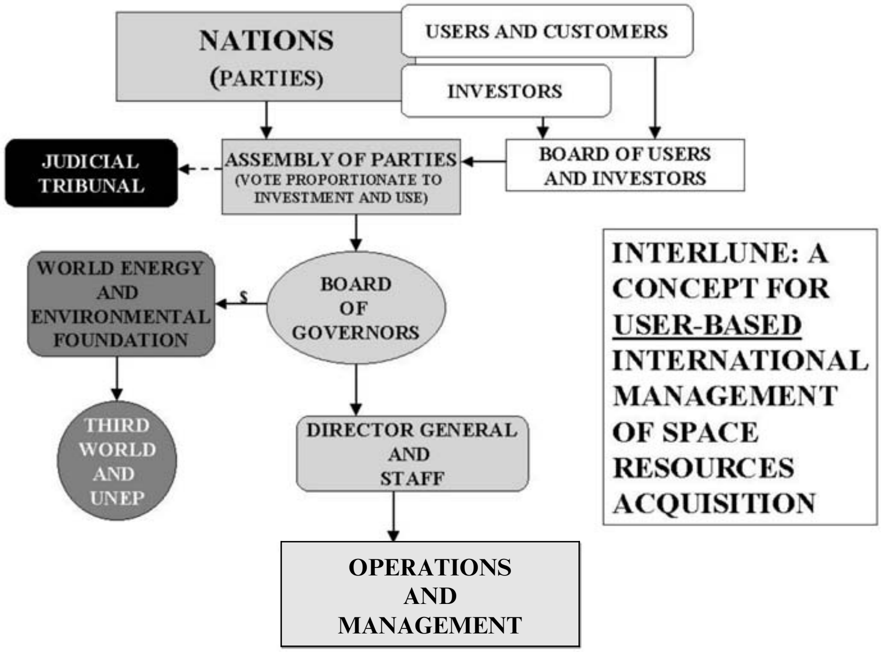

FIGURE 8.3 A diagrammatic representation of a hypothetical "Interlune" organization based on an Intelsat model for international management of lunar resource production (after Schmitt – see note 3).

4. *Private/United States government partnership.*[4] This combination of private and government financing and management gives the government the responsibility for establishing a lunar base that would support activities by other entities. A clear commitment by the government to such an endeavor should trigger the release of previously committed private funds for investment in the development of lunar resource recovery technology and terrestrial fusion power based on helium-3. Conversely, such committed private funds should help to catalyze the government's commitment to a lunar base.
5. *Private/Government-funded lunar RDT&E.*[5] The government's role in this alternative combination of private and government commitments would consist of government financing of the private entity's research and development, test and evaluation (RDT&E) of lunar resource recovery technology. With the government clearly committed, investors might provide the remaining funds necessary for booster development, fusion power demonstration, and overall management.
6. *All-private.*[6] An all-private approach would depend solely on private financing and management. A critical component of this approach is

> the near-term commercialization of fusion technologies that could serve existing markets for low-cost sources of neutrons and protons. As with most private business initiatives, the primary role of the United States government would be in the negotiation and enforcement of regulations and as an advocate for enabling interpretations of international treaties. The government would also be a potential customer of lunar resources, fusion power plants, fusion rockets systems, and spinoff technologies.

Two of the possible approaches listed in Figure 8.2 are not evaluated here as being basically unworkable in the context of complex and time-critical space operations. The "international, one nation–one vote" approach would so politicize decision-making that it would stagnate. The "multilateral consensus model" would not permit the making of the time-critical decisions that are an inherent part of deep space operations.

8.2 FINANCING

The most critical initial determination in the evaluation of the feasibility of a lunar resources and helium-3 fusion power initiative lies in consideration of the potential for attracting adequate financing. Table 8.1 gives a relative ranking (10 being the highest ranking and 1 being the lowest) of the six alternative approaches described above with respect to the major financial issues that would face any such enterprise. An additional qualitative weighting factor of 3 has been given to the five financing elements (indicated by an asterisk ⋆) deemed most important to the initial and continuing success of the enterprise, namely, (1) minimum start-up capital required, (2) maximum financing feasibility, (3) minimum operating costs, (4) maximum return on investment, and (5) maximum staying power. Minimum cost of capital (indicated by #) has received a weighting factor of 2.

8.2.1 Minimum start-up capital required (weighting = 3)

Probably the most practical and politically sensitive requirement for a lunar resource enterprise is that for start-up capital, defined here as the financing necessary to reach the point of first delivery of lunar helium-3 to the first online helium-3 power plant on Earth. This requirement has been estimated to be about $15 billion for the all-private approach,[7] although much conceptual and then detailed hardware design work will be required before this figure is verified or modified. More detailed rationales for this

TABLE 8.1 Financial ranking (estimated) of six approaches to managing a return to the Moon (1 = All-US government, 2 = Multilateral model, 3 = Intelsat model, 4 = Private/Government partnership, 5 = Private/Government-funded lunar RTD&E, and 6 = All-private).

		Approaches (Section 8.1)					
Financing issue(1)	Weight	1	2	3	4	5	6
⋆Minimum start-up capital required(2)	3	9	6	3	15	21	30
Minimum tax revenues required	1	1	2	5	6	8	10
Minimum private capital required	1	10	10	8	3	2	1
#Minimum cost of capital(3)	2	20	20	20	14	10	2
⋆Maximum financing feasibility	3	3	6	12	12	15	30
Least regulatory costs	1	8	9	10	7	5	1
⋆Minimum operating costs	3	9	3	6	15	27	30
⋆Maximum return on investment(4)	3	12	6	3	18	24	30
⋆Maximum staying power	3	3	6	15	6	18	30
Financial subtotal		**75**	**70**	**82**	**96**	**130**	**164**

Notes:

(1) ⋆ gives factor of 3 weighting and # gives factor of 2 weighting.

(2) Start-up capital is defined as that financing necessary to reach the point of first delivery of lunar helium-3 to the first online helium-3 fusion power plant on Earth.

(3) Cost of capital is assumed to be equivalent to the interest on the national debt for approaches involving US government funding and to range from low to medium to high for approaches with increasing need for private financing.

(4) Total Return on Investment (ROI) for taxpayer-funded cases relates to value of (a) spinoff technologies, (b) reduced cost of electrical power, (c) reduced import dependence, and (d) environmental benefits. ROI for privately funded cases relates to investor returns, the above four factors, and added tax revenues to government.

estimate are made in Chapters 4–7 and 11 of this book. It can be safely assumed, based on past history of commercial versus governmental initiatives, that the start-up capital required for an all-private approach will be significantly less than that required for other approaches involving either international participants or the United States government. This assumption is due to governments' inherent bureaucratic inefficiencies and low economic incentives to succeed. A multinational, Intelsat approach probably would require the most start-up capital due to the need to satisfy all the national interests involved.

8.2.2 Minimum tax revenues required (weighting = 1)

All approaches to a lunar resources and helium-3 fusion power initiative considered here will involve the participation of the American taxpayers, ranging from full funding of an all-US government approach, to partial funding of other approaches, to oversight of regulatory and treaty activity related to an all-private approach. Clearly, an all-private initiative will require the least tax revenues for its support and an all-US government effort the most. The issue of the tax revenue requirement is included in the evaluation because tax revenues spent on government activities related to this enterprise will not be available for other potential government spending and thus could be considered a negative factor. Although largely funded by tax revenues, some private investment capital would be sought in the Intelsat model approach, thus potentially reducing the tax revenues required.

8.2.3 Minimum private capital required (weighting = 1)

Private capital requirements are roughly the reverse of tax revenue requirements, obviously reaching their maximum in those approaches involving a mostly private sector initiative. One could be viewed as largely canceling out the other in this evaluation. It is highly unlikely, however, that an all-private approach would require more private capital than either of the combined private/government approaches when one considers the inefficiencies that would be introduced by the complexities of managerial interactions.

8.2.4 Minimum cost of capital (weighting = 2)

Mitigating to some degree the greater start-up capital (tax revenues or addition to national debt) required for approaches to a lunar resources and helium-3 fusion power initiative involving international or United States government entities, the effective cost of capital for such approaches would be the marginal cost of new national debt or the cost of **not** paying off the highest cost debt with the same capital. Either of these costs of capital would be less than the cost of private capital not guaranteed by the government. An all-private approach thus would be perceived to be a higher risk, neglecting the uncertainties in the continuity of congressional or White House support of a government initiative. In approaches involving the government as a partner or subsidizer of a private initiative, the cost of private capital probably would be less than for the all-private approach because of the perception that government's participation lowers any risk. This perception would probably not prove to be valid if we consider the potential for administrative or legislative withdrawal of government support, as has happened to large projects in the past.

8.2.5 Maximum financing feasibility (weighting = 3)

Ultimate feasibility of actually obtaining financing will always loom as the most practical and also the most subjective issue of any evaluation of approaches to financing a lunar resources and helium-3 fusion power initiative. Increasing political pressures to reduce discretionary spending of tax revenues by all governments in favor of increased spending on social entitlement programs vastly reduce the feasibility of gaining significant United States government or international financing for space- and energy-related programs. Even though the case for all-private financing has yet to be proven, the potential of making that case appears much greater (see Chapter 11) than convincing governments to allocate the necessary budgetary resources, at least for the foreseeable future. Commercial satellite communications, dot-com endeavors, biomedical start-ups, and computer chip technology businesses illustrate the potential for raising large amounts of investor capital for technology ventures. The feasibility of government financing increases as the level of risk is shared with international or private partners, but it remains significantly below that of an all-private approach where returns on investment are possible from spinoff technologies.

8.2.6 Least regulatory costs (weighting = 1)

The least regulatory costs could be expected for international approaches to a lunar resources and helium-3 fusion power initiative due to both less environmental concern in most other nations than in the United States, their trade and politically motivated support of the Kyoto Climate Treaty notwithstanding. Once international commitments are made, there would also be greater pressure to continue the initiative. This latter pressure has been evident in recent years – for example, in the case of the International Space Station. On the other hand, under the current situation in the United States, the all-private approach will see the highest regulatory costs due to the ease by which excesses in litigation and federal enforcement against private entities occur as compared to other approaches. This situation leads to private entities erring on the side of regulatory and litigation caution, thus raising costs. A lunar helium-3 initiative, however, will ultimately be less subject to environmental regulation than other power technologies.

8.2.7 Minimum operating costs (weighting = 3)

The long-term economic success of a lunar resource and helium-3 fusion power enterprise will rest on the approach that results in the lowest operating costs. History clearly shows that the profit incentives inherent in an all-private approach, competing with other sources of twenty-first-century electrical power, will force the lowest operating costs commensurate with staying in business and with customer satisfaction. Few, if any, long-term examples exist of the United States government or international entities providing an unsubsidized service at total operating costs lower than private entities offering a similar service. Even the early successes of user-based organizations like Intelsat and Inmarsat, providers of international telecommunications, have not been sustained in a competitive marketplace. Efforts leading to the privatization of both organizations have been underway for several years and appear to be approaching culmination.

8.2.8 Maximum return on investment (weighting = 3)

A true return on investment (ROI) only relates directly to approaches that attract actual investors, private or public, and the higher the risk, the higher must be the ROI from the enterprise. At various times in their financial histories, most major technology initiatives have brought high returns to early investors. Such successful initiatives include the early East Indies spice trade, shipping by clipper ship, the railroads, petroleum production, mass production of automobiles, telecommunications, computers and computer software, and pharmaceuticals. On the other hand, an indirect form of ROI results in several ways if any approach is successful: (1) from the taxes paid by participants in successful initiatives, whether individual employees, investors, or companies; (2) from the less easily quantifiable environmental, technological, and economic benefits consequential to a successful venture; and (3) from the spinoff technologies that inevitably come from complex technological endeavors. The all-private approach clearly combines both the direct and indirect ROI, but, in this evaluation, some level of indirect ROI must be allocated to all other approaches, if successful.

8.2.9 Maximum staying power (weighting = 3)

Once a lunar resources and helium-3 fusion power initiative begins, the most critical issue becomes the staying power of a particular financing and managerial approach – although, over time, a major private initiative may get long in the tooth and lose sight of what best serves its investors.

Alternatively, government may decide to punish success or to deal necessarily with private irresponsibility. Antitrust breakups, regulatory controls, and criminal prosecution have ultimately resulted in a loss of private continuity and investor confidence in many previously successful corporations. The early and mid-histories of many such initiatives, however, have shown remarkable financial and operational continuity. The establishment and maintenance of strong management systems and professional ethics can preserve such performance. In the last century, this staying power has existed in industries related to mining, steel, energy, transportation, telecommunications, and pharmaceuticals.

History suggests that one of the least reliable entities of "staying the course" is, unfortunately, any governmental organization. This unreliability has been demonstrated by examples of projects such as the superconducting super-collider, coal gasification, commercial alternative energy systems, fission waste reprocessing, and many recent NASA, DOD, ESA, and UN undertakings.[8] This lack of dependability, reflecting both the politics and the budget pressures discussed above, manifests itself particularly in the case of initiatives related to science and technology, such as advanced power systems development, high-energy physics research, basic research in general, and many advanced national defense systems. An interesting exception is deuterium–tritium fusion research by many nations, which has continued to be supported in spite of not delivering on its promises over many decades. Approaches dependent entirely or in large part on the participation of government organizations therefore are downgraded in the evaluation given here. The staying power of individual governments, such as the United States, improves somewhat with the involvement of partners, international or private, and when the government's role is limited to a narrow supporting role that could be assumed by partners after some critical phase has passed.

8.3 MANAGEMENT

The next set of critical issues in the evaluation of a lunar resources and helium-3 fusion power initiative relate to an evaluation of its potential for managerial success. Table 8.2 shows a relative ranking with respect to the major management issues (10 being the highest ranking and 1 being the lowest) of the six alternative approaches defined earlier. An additional qualitative weighting factor of 3 has been given to three management elements (indicated by an asterisk *) most critical to the continuing success of the enterprise, namely, (1) minimum complexity of management, (2) maximum sales margins, and (3) motivation of workforce. Several other management issues of slightly less criticality (indicated by a pound sign #) have received a weighting factor of 2.

8.3.1 Minimum complexity of management (weighting = 3)

Complexity of management constitutes an issue upon which rides the success or failure of any enterprise, much less that as inherently complicated as a lunar resource and helium-3 fusion power initiative. Any approach can fall victim to overly complex management, but the more the influence of private investors is a factor, the greater are the incentives to reduce complexity and thus reduce costs. Conversely, the more government players involved in a given approach, the greater the tendency towards complexity caused by bureaucratic interactions.

8.3.2 Minimum complexity of operations (weighting = 2)

The same considerations that drive evaluations of the complexity of overall management drive evaluations of the complexity of operations within the various approaches considered here, only more so. The more government is involved in routine operations, the greater the tendency toward bureaucratic complexity and inefficiency. One only needs to contrast the histories of service industries run by the private sector with comparable, less successful activities run or subsidized by the United States government. Consider, for example, the package delivery business versus the United States Postal Service, commercial satellite communications versus the previously subsidized Intelsat and Immarsat corporations, the well-maintained private toll roads versus the deteriorating Interstate system, commercial broadcast and cable systems versus the subsidized Public Broadcast System and National Public Radio, and, most importantly, private schools versus the abysmal public school system. Similar examples exist elsewhere, particularly in Europe. Flourishing black markets in all largely socialist or high-tax countries make the same point that, with few exceptions, services are better provided by a properly refereed private sector than by government alone.

8.3.3 Access to largest technical base (weighting = 1)

In theory, all approaches to a lunar resource and helium-3 fusion power initiative should have access to the same worldwide technical base; however, those approaches that involve cooperation by a number of developed nations may have a significant advantage. An all-private approach would be a close second, depending on how broadly it spread its subcontractor net to involve international entities. Approaches involving government fall behind others due to government's tendency to control intellectual property rights, thus reducing the incentives or raising the cost for the participation of commercial entities. (An exception is found in the retention and potential commercialization of intellectual property by American universities and colleges through the Bayh–Dole Act.)

8.3.4 Quality in planning, RDT&E, production, and operations (weighting = 2)

Considerations of quality in planning, RDT&E (research, development, test and evaluation), production and operations for the various approaches closely track the evaluations for complexity in management, although the Intelsat model ranks somewhat higher in planning and RDT&E as it is assumed that these functions will be one of those performed under contract to a single commercial business. On the other hand, international approaches have difficulty *not* distributing responsibility for necessary hardware and operations among its participating members based on political considerations, thus inherently limiting access to maximum efficiency and quality.

8.3.5 Quality in marketing and sales and product distribution (weighting = 1)

Marketing and sales and product distribution by a lunar resources and helium-3 fusion power initiative will directly or indirectly be part of all approaches and their quality will affect a given approach's ROI, irrespective of how that parameter might be measured. The long-term rate of growth of the enterprise will depend initially on demand for competitive and clean electrical power, and later on demand for resources in space. Further, investor and public perception of success will be determined in part by how effectively lunar resources reach power and space customers. We can expect that those approaches that are dependent on private sector management of marketing and sales and product distribution will significantly outperform the others, with the Intelsat model approach being the best of the others.

8.3.6 Maximum sales margins (weighting = 3)

As with any business, ultimate viability depends on gross sales margins – that is, the percentage by which revenues exceed costs over the long haul. Approaches involving the private sector, again, will be more focused on

TABLE 8.2 Management ranking (estimated) of six approaches to managing a return to the Moon (1 = All-US government, 2 = Multilateral model, 3 = Intelsat model, 4 = Private/Government partnership, 5 = Private/Government-funded lunar RTD&E, and 6 = All-private).

		Approaches (Section 8.1)					
Management issue[1]	Weight	1	2	3	4	5	6
*Minimum complexity of management	3	9	3	6	12	18	30
#Minimum complexity of operations	2	12	2	4	8	18	20
Access to largest technical base	1	1	3	10	5	7	9
#Quality in planning	2	12	2	8	14	16	20
#Quality in RDT&E[2]	2	14	2	12	14	16	20
#Quality in manufacturing	2	14	2	6	16	18	20
#Quality in operations	2	16	2	12	18	20	20
Quality in marketing and sales	1	1	1	6	10	10	10
Quality in product distribution	1	1	1	6	10	10	10
*Maximum sales margins[3]	3	3	3	12	21	24	30
#Quality in financial controls	2	3	1	3	5	10	10
#Quality of workforce	2	14	2	12	16	18	20
*Motivation of workforce	3	21	3	18	24	27	30
Management subtotal		**120**	**27**	**115**	**173**	**212**	**249**

Notes:

(1) * gives factor of 3 weighting and # gives factor of 2 weighting.

(2) Research, development, test, and evaluation.

(3) Assumes no subsidies.

maximizing this parameter than will others in order to satisfy investors. The best of the others, again, will be the Intelsat model approach.

8.3.7 Quality in financial controls (weighting = 2)

For better or worse, the regulatory and investor generated pressures on an all-private approach, requiring the creation and maintenance of financial controls, will always be greater than the pressures that governments impose on themselves. For this reason, an all-private approach to a lunar resource and helium-3 fusion power enterprise ranks significantly higher than others relative to financial controls, although their costs in this regard also will be higher.

8.3.8 Quality of workforce (weighting = 2)

The quality of the workforce for any approach to a lunar resource and helium-3 fusion power initiative will be high due to the emotional attraction young men and women have for space-related activities. The added financial and ownership incentives that can be brought to bear on hiring by an all-private approach will give that approach an additional advantage.

8.3.9 Motivation of workforce (weighting = 3)

If anything ranks higher than the quality of the workforce, it is motivation of that force. Again, all approaches to a major space enterprise can draw on highly motivated young men and women. The greater probability of success inherent in an all-private approach, however, and the potential of ownership in the fruits of that success, can always be expected to increase that already high level of motivation.

8.4 EXTERNAL ISSUES

Finally, several external issues need to be evaluated to determine the long-term political support that a lunar resource and helium-3 fusion power

TABLE 8.3 External issues ranking (estimated) of six approaches to managing a return to the Moon (1 = All-US government, 2 = Multilateral model, 3 = Intelsat model, 4 = Private/Government partnership, 5 = Private/Government-funded lunar RTD&E, and 6 = All-private).

		Approaches (section 8.1)					
External issue(1)	Weight	1	2	3	4	5	6
⋆Maximum net environmental protection	3	24	3	15	24	30	30
Maximum potential for technology spinoff	1	1	2	5	7	6	10
#Maxiumum economic benefit	2	10	2	6	14	16	20
⋆Maximum world benefit	3	3	3	24	3	3	30
#Maximum potential for space settlement	2	2	2	10	9	14	20
External issues subtotal		**40**	**12**	**60**	**57**	**69**	**110**

(1) ⋆ gives a factor of 3 weighting and # gives a factor of 2 weighting.

initiative can enjoy. Table 8.3 shows a relative ranking (10 being the highest ranking and 1 being the lowest) of the six alternative approaches evaluated in Tables 8.1 and 8.2 with respect to the major external issues. An additional qualitative waiting factor of 3 has been given to the two external issues most critical to the continuing success of the enterprise, namely, (1) maximum net environmental benefit and (2) maximum benefit to people in developing nations. Maximum benefit to the overall United States' economy and maximum potential for space settlement have each received a weighting factor of 2.

8.4.1 Maximum net environmental protection (weighting = 3)

In many minds, the most important consequence of the success of a lunar resources and helium-3 fusion power initiative will be gradual replacement of electric power plants that rely on fossil fuels or nuclear fission through normal retirement of such plants or the satisfying of new power demand. Independent of the current controversy over potential climate change due to power plant and other fossil fuel emissions, the long-term demand for natural hydrocarbons as chemical feed stocks to meet expanding human needs makes a successful helium-3 initiative additionally important. The proven ability to rapidly introduce a new, cost and environmentally effective, technology into an existing marketplace gives an all-private approach a strong edge over those with a significant government involvement, and a particularly strong edge over international approaches in which environmental issues traditionally play a political rather than a practical role.

8.4.2 Maximum potential for technology spinoff (weighting = 1)

The all-private approach to a lunar resources and helium-3 fusion power initiative has the need to develop early applications of related technologies in order to establish a foundation for early returns on investment that will attract additional investor capital (Chapter 11). This need for early bridging capital, as well as for long-term profits, would stimulate the consideration of new technical approaches that may include potential spinoffs as well as provide lower capital costs for ultimate power applications.[9] Conversely, several governments of the world, including the United States, have made major financial and policy commitments to fusion and space-related technologies (Tokamak-based fusion, inertial confinement fusion, Space Shuttle, and the ISS) that have limited direct commercial spinoff potential and have high capital and operating costs.

Further, the tendency of many governments to retain and, in some cases, confiscate intellectual property rights inhibits spinoff of new technology into the commercial sector. Indirect, component level spinoffs occur at significant rates only if permitted by the policies of specific agencies or governments. Indeed, throughout Apollo, NASA's policy bias toward rapid technology transfer to the private sector stood in sharp contrast to the highly restrictive policies in effect at the Department of the Interior and the Department of Energy and its predecessor, the Atomic Energy Commission. This contrast in policies, for example, resulted in the rapid transfer of the improved electronic and energy conversion technologies needed for Apollo and very restrictive availabilities of new energy production technologies. On the international scale, a similar contrast existed between the potential for broad applications of early space technologies by the dynamic consumer marketplace of the United States versus the nearly non-existent discretionary consumer marketplace of the then Soviet Union.

In the final analysis, governments in general do less well historically at providing spinoff benefits to their populations than do private initiatives. This tendency can be overcome in large part by well-conceived, cooperative private–government efforts (Chapter 1) best illustrated in the fields of transportation, agriculture, and medicine.

8.4.3 Maximum economic benefit (weighting = 2)

Major initiatives provide the maximum benefit to the United States and other economies when they are combined with aggressive incentives to be successful at the minimum cost and maximum profit within an appropriately regulated business environment. These incentives lead to several broad economic benefits: (1) less competition for capital, (2) profits re-entering the economy, (3) spinoff technologies supporting new business and employment, (4) a shorter time to commercialization, (5) minimum need for taxpayer-supported funding, (6) a new arena for the generation of trade benefits, and (7) a huge new source of tax revenues. Such benefits favor the all-private approach to a lunar resources and helium-3 fusion power initiative over all others.

8.4.4 Maximum world benefit (weighting = 3)

Treaty obligations (Chapter 12) suggest that space resources should benefit all nations, as well as contribute to long-term international stability. This argues strongly for the benefits of a lunar resources and helium-3 fusion power initiative to flow to all humankind commensurate with continuing success of the enterprise.[10] On its face, one might argue that international approaches would fill this requirement best. An all-private approach would be better than others, however, because of the greater likelihood of success, a clear market incentive to spread the benefits of fusion power worldwide, and a similar market incentive to facilitate the rapid education of all nations about those benefits. The Intelsat model, properly implemented as it was in its beginnings, might provide worldwide benefits on a level comparable to an all-private approach. On the other hand, the all-private approach would provide these benefits more quickly, simply due to the overall efficiency of management. Eventually the Intelsat model would not be able to compete, as was finally discovered even in the provision of international telecommunications.

Several models for transferring the benefits of helium-3 fusion power to the peoples of the world should be considered. For economies that can afford either full purchase or debt financing, private or public ownership of a fusion plant may make sense. In all such cases, contracts would call for the selling entity to provide for initial construction and operation, but with commitments to train indigenous peoples to gradually take over operation and responsibility for eventual decommissioning. For others, the purchase of power may be preferred with the owner of the plant retaining responsibilities for construction, operations, maintenance and decommissioning. This last approach may make the best business financial sense for a private initiative, but may not be preferred by the customer. If the customer desired, an option for training and eventual plant purchase could be included with the contract for power.

8.4.5 Maximum potential for space settlement (weighting = 2)

An ultimate benefit to humankind from a lunar resources and helium-3 fusion power initiative will be its inherent potential to catalyze human settlement away from Earth. First of all, the initiative needs permanent habitation on the Moon to minimize operational costs. In addition, the immense technology base arising from such an initiative, the space life-supporting by-products of helium-3 production on the Moon, and helium-3 fusion technology adapted to interplanetary rockets[11] will enable broad scale use of space stations, the initial settlement of Mars, the diversion of asteroids from a collision course with Earth, and human travel elsewhere in the solar system and possibly into the galaxy. The greater overall probability of success and the inherent ability to provide ownership incentives to lunar settlers suggests that an all-private approach maximizes the potential for future space settlement and deep space exploration.

8.5 AGGREGATE APPROACH EVALUATION

The aggregate evaluation of the financing, managerial, and external issues facing the six approaches to a lunar resources and helium-3 fusion power initiative is given in Table 8.4. Relative to other approaches, an all-private approach has a strongly favorable aggregate evaluation as well as leading in each of the three issue areas examined. A private initiative would have the additional advantage of being less subject to political and media second-guessing than would those approaches that heavily involve the government.

TABLE 8.4 Aggregate rankings for six approaches to managing a return to the Moon (1 = All-US government, 2 = Multilateral model, 3 = Intelsat model, 4 = Private/Government partnership, 5 = Private/Government-funded lunar RTD&E, and 6 = All private).

	Approaches (Section 8.1)					
Issue area	1	2	3	4	5	6
Financing issues	75	70	82	96	130	164
Management issues	120	27	115	173	212	249
External issues	40	12	60	57	69	110
Aggregate rankings	**235**	**109**	**237**	**326**	**411**	**523**

Combined private and US government approaches follow a private approach in the aggregate evaluation. Of the approaches that include international participation, the Intelsat model appears to be the most desirable. The least attractive approach in this evaluation, not including a one nation–one vote organization, is a US-government-led international consortium comparable to the International Space Station.

Clearly, this aggregate evaluation of the six approaches has little foundation in quantitative statistics, as each individual issue evaluation is purely subjective. Indeed, other approaches and other issues might be considered in a more detailed analysis. On the other hand, the sensitivity of the aggregate conclusion to changes in the relative evaluations for each issue is not great. Only a major unknown factor, such as the United States government's unwillingness to sanction an all-private approach, could change the overall conclusion that such an approach has the greatest chance of success.

These evaluations therefore support an aggressive effort to define a business plan based on an all-private initiative and to insure that the political and legal environments encourage and do not preclude such an approach to lunar resource and helium-3 fusion power development. Initial steps to build a business plan are outlined in Chapter 11. As the United States government has announced a new Moon–Mars initiative, however, the requirements to manage such an initiative are discussed in Chapter 10. A non-controlling, research and technology development partnership between the government and a private initiative would clearly be advantageous to both, as historically was the case in aeronautics, agriculture, and medical science.

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9

MANAGEMENT: LESSONS FROM APOLLO

9.1 INTRODUCTION

APOLLO demonstrated that management constitutes the most critical component of a human Return to the Moon and eventually of humans going on to Mars. An understandable tendency exists in government and the media to concentrate on advancement of technology; however, management and leadership of the creation, integration, and operation of that technology is demonstrably even more important. The history of terrestrial exploration and pioneering illustrates this truism equally well. The remarkably successful voyages of the British research ships the *Challenger* and *Beagle*, the Lewis and Clark expedition, Roald Amundsen's trek to the South Pole, and Fridtjof

Nansen's North Polar Expedition – and even Ernest Shackelton's failed attempt to cross Antarctica – document the critical importance of management: good planning, preparation, implementation, and leadership. The tragic consequences of the lack of planning and preparation are also recorded in Robert Falcon Scott's expedition's failure and death in Antarctica.

NASA's history of initiatives since the early 1970s demonstrates the consequences of poor management as much as it shows the wonders of space technology and the courage of those who use it. NASA's failures and cost overruns, unfortunately, cloud its successes. In contrast, although Apollo's technology at the component level, for the most part, represented the best available during the 1960s, it clearly is not what could be available today. On the other hand, the Apollo management system made it possible for that 1960s base of know-how to land human beings "on the Moon and return them safely to Earth."[1] Lessons from this success should be carried forward into any new endeavor to Return to the Moon or go beyond.

9.2 APOLLO MANAGEMENT

9.2.1 Evolution of an approach to management

The implementation of Project Mercury, the development and implementation of Project Gemini, and the planning, design, and development of Apollo fully occupied NASA and most of its research, development, and operational centers during the period 1961–1966. It was a heady time of long days and long nights that would continue to the end of the Apollo Program in December 1972. It also was a time when engineers learned what they did not know about spacecraft and rocket design, when a management system was taking form, and when flight controllers and astronauts were gaining hands-on experience in space. The reader is referred to the many personal stories[2] and historical accounts[3] for the details and excitement of this remarkable period.

From the beginning of NASA, it was clear that the complexity of deep space operations required a competent and disciplined management culture. T. Keith Glennan, the first NASA Administrator, laid much of the foundation on which such a culture eventually developed.[4] Within a few months of assuming the position of Administrator, he started a search for a "general manager." This person would be the number three person in the Agency after Deputy Administrator Hugh Dryden, former head of the National Advisory Committee on Aeronautics (NACA) from which NASA was formed. The general manager would have the title of "Associate Administrator" and would run the day-to-day operations of NASA, including general oversight of the field centers. Glennan, in turn, would be responsible for the bureaucratic and political challenges of dealing with other governments, other agencies and departments, the Congress, and the White House while Dryden would be the "technical center" at Headquarters.[5] Glennan and NASA were fortunate to start with two excellent Associate Administrators, beginning with Richard E. Horner, a career aerospace manager with the Army and then the Air Force before joining NASA in June of 1959. Horner was followed by Dr Robert C. Seamans Jr.[6] Seamans had been an aeronautical engineer at MIT and RCA when he took over in September 1960.

The creation of a strong Headquarters management team for manned space flight was critical even before Kennedy totally embraced Apollo. When he became Kennedy's Administrator in March 1961, James E. Webb followed up on one of Glennan's departing suggestions and ordered that the field centers report directly to Associate Administrator Seamans rather than through lower staff offices at Headquarters.[7] Seamans filled this role, including managing the centers' ramp-up in budgets and personnel, until September 1961 when D. Brainerd Holmes became Associate Administrator, under Seamans, for the newly formed Office of Manned Space Flight. Holmes, an engineer, had been project manager for RCA on the missile early warning system in the Arctic. Holmes added further strength to Headquarters' oversight of manned space development with the hiring of Joseph F. Shea from Space Technology Laboratories as his deputy for systems engineering. Along with Shea at the senior level, Holmes inherited George M. Low, formally at the Lewis Research Center, who had been deeply involved in manned space flight planning since early 1958.[8]

Apollo's success, in retrospect, can be tied back to a relatively small number of highly significant, early managerial decisions related to the program's implementation. In November 1958, NASA formed a "Space Task Group" under Robert R. Gilruth at the Langley Research Center to oversee the Mercury "man-in-space" project[9] and, with Low at Headquarters, to coordinate planning for other manned space activities. In December 1961, Holmes's team formally authorized Gilruth to go forward with the planning and development of a follow-on program to Mercury, or what became Project Gemini.[10] With most eyes on Gemini, and its testing of many of the operational procedures for Apollo, the decision on where to locate the management center for manned spacecraft activities took on added importance. The Goddard Space Flight Center in Greenbelt, Maryland, had originally been built to received Gilruth's Group after the Mercury Project was finished. But, in September 1960, Glennan, apparently influenced by newly appointed Associate Administrator Seamans, decided that Gilruth's Space Task Group should have its own separate field center.[11] In September, a year later, Webb selected Houston as the site of the new center, designated the Manned Spacecraft Center, based in part on community enthusiasm[12] and the interest of Albert Thomas, chairman of NASA's Appropriations Subcommittee in the United States House of Representatives,[13] an interest matched apparently by Vice President Johnson, also a Texan. An adjunct to this decision was that "Houston" would be the location of the integrated Mission Control Center, resulting in the familiar opening address used almost invariably by the astronauts in their radio calls from space.

Several other early line management decisions also later became important to the eventual success of Apollo. As head of the Space Task Group, Gilruth made the decision to contract with private companies for the conceptual design studies related to the Mercury Project, the first step in contracting out most future research, development, and manufacturing for space hardware. This approach had become the twentieth-century tradition for buying military systems and was now going to be the rule with space systems. By not bringing most of such work "in house," – that is, making the "make or buy" decision in favor of "buy" – NASA tapped a broad reservoir of national capability, particularly in the aircraft, missile, and electronics industries.

Further, Christopher C. Kraft, the Mercury launch and flight director, insisted that decisions made by him, and future launch directors and flight directors assigned to manage the actual operations of a specific mission, could not be overruled by more senior managers.[14] These directors could be fired after the fact, but during a mission, Kraft demanded that they must have full authority, and his boss, Gilruth, and their boss, Glennan, concurred. This precedent established both the clear line of authority during actual space operations and the decision-making discipline necessary to maximize both safety and the probability of success. Gilruth also made a number of other decisions to evaluate engineering issues inside his group.[15] Of similar importance was Max Faget's 1959 maneuver to provide an internal NASA design for the Mercury capsule in competition with those of industry contractors. This assured, at least through Apollo, that there would be a core of competent designers in NASA working in parallel with the contractors.[16] The existence of that core had several highly significant benefits. It created the capacity for writing detailed and internally consistent contract specifications, for evaluating the technical quality of competing contractor bids, for monitoring and managing contract performance, and for providing backup approaches in the event that original engineering concepts proved inadequate. These internal engineering teams, working in parallel with contractors, also provided mid-level managers with two independent points of view on technical issues. Although uncomfortable at times, the resulting tension between competing professional teams gave a much more comprehensive vetting of the tradeoffs and nuances involved with a given issue or recommended design change.

In the early years of NASA there was a gradual evolution of a concept for parallel design engineering for capabilities deemed particularly critical to successful space flights. Competitive approaches to achieving such capabilities would often be funded in industry or between industry and NASA center engineers. At various times, when the originally selected technical approach did not ultimately meet specifications or its test objectives, a competing approach would be brought forward and used instead. One of the more illuminating examples of this was the decision to replace the original design of the Lunar Module ascent engine with a different design within about six months of its first use in space[17] (Apollo 9 in March 1969) and about 10 months before committing to its use to lift Armstrong and Aldrin off the Moon.

Early engineering decisions also precluded hardware and software designs that allowed catastrophic, "single point failures." In this same spirit, Kraft and Eugene F. Kranz imbedded within the concept of "mission rules" the philosophy that, should one failure occur that exposed the mission to a potentially catastrophic single point failure, the mission plan would be revised to eliminate that condition. Kraft's NACA aircraft test flight activities had shown the wisdom of developing such mission rules, along with mission timelines, before a mission flew rather than at the time an emergency demanded them. Mission rules provided not only discipline in decision making during flight emergencies, but became a critical component in the detailed planning for mission operations and training.

Once Kennedy had issued his historic challenge to go to the Moon, a variety of other engineering, operational, and management decisions led to an increase in the payload capacity and operational flexibility of the lunar lander. For example, a fundamental issue was how to maximize the value of the Saturn lift capability. In early 1961, there was a debate within NASA about the "mode" or broad operational approach that would be used to land on the Moon.[18] The early landing mode discussion had been gradually narrowed down to a choice between two alternatives. The first was to launch directly to the lunar surface, the so-called "direct approach," favored by the Space Task Group at Langley and then Houston. One late version of the direct approach included a "lunar crasher" in which the descent propulsion stage would be jettisoned just prior to landing.[19] The other alternative was known as the "Earth-orbit rendezvous mode," supported by von Braun's group at Huntsville. The latter mode would involve the use of several launches and multiple rendezvous in Earth orbit to assemble a combined lander and return vehicle that would fly directly to the lunar surface then return to Earth. A third approach, the "lunar-orbit rendezvous mode," under development by John C. Houbolt of Langley, was just beginning to be discussed.[20] The "lunar-orbit rendezvous mode" would consist of a single launch of a combination of several specialized spacecraft stages, each of which would be discarded as their portion of a mission was completed, culminating with a rendezvous in lunar orbit for the return home.

Administrator Webb's July 1962 announcement of the choice of the lunar-orbit rendezvous mode was due to the persistence of a single engineer at the Langley Research Center, John Houbolt. As the debate raged on this subject, there gradually developed a rare confluence of joint advocacy by the Marshall Space Flight Center and the Manned Spacecraft Center, particularly on the part of their directors, von Braun and Gilruth, respectively. The decision to add a fifth engine to the Saturn, and thus to become the "Saturn V,"[21] appears to have played a significant role in convincing Gilruth that this lunar-orbit rendezvous would be the best approach.[22]

The lunar-orbit rendezvous decision provided much needed focus to the launch vehicle and spacecraft development activities at the Huntsville and Houston centers. It ultimately resulted not only in an increased landed payload on the Moon, but, except for the docking interface between the two primary spacecraft, the decision largely decoupled the work on the Command and Service Module at North American from that on the Lunar Module at Grumman Aircraft. Similarly, largely separate mission control teams could now manage the flight operations of the two spacecraft, thus also simplifying that part of planning, preparation, and training. Although many trials still awaited NASA before the first lunar landing was accomplished, the wisdom of the choice of lunar-orbit rendezvous became increasingly obvious as the years passed.

The first of several key managerial changes occurred in June 1963. At that time, George E. Mueller (pronounced "Miller"), TRW's vice president for Research and Development, replaced Holmes as Associate

Administrator for Manned Space Flight.[23] Long festering disagreements between Webb and Holmes on the proper balance between achieving a Moon landing as soon as possible and other NASA activities led to this change. Holmes had advocated a more aggressive approach to the lunar landing program rather than the "balanced" approach to manned and unmanned projects supported by Webb. Needless to say, Holmes lost this argument, establishing a tradition for NASA to be more than just a single-purpose agency. As post-Apollo history has shown, this multifaceted character of NASA has proved to be a serious distraction for the Agency and its Centers in their competition over budgets and personnel. (Challenging this status quo is one of the consequences of the 2004 Moon–Mars initiative proposed by President Bush.)

Mueller's appointment, with Bob Seamans as the Associate Administrator and Homer E. Newell as Associate Administrator of Space Science, completed the definition of the senior Headquarters team that would oversee Apollo. Mueller also quickly hired the Minuteman missile program manager, Air Force Brigadier General Samuel C. Phillips, as Apollo Program Manager. This core of Mueller and Phillips would stay in place through Apollo 11, the first lunar landing. The pair also would have approved the essential elements of the expansion of Apollo into a lunar exploration program. An important adjunct to this team was Raymond L. Bisplinghoff who was Associate Administrator for Advanced Research and Technology and oversaw the key research engineering teams at the Lewis, Ames, and Langley Research Centers.

The single most important managerial decision at the Center level relative to the future of Apollo was probably Gilruth's creation of the Apollo Spacecraft Project Office (ASPO, pronounced "ass-po") in the spring of 1962. Headed initially by Charles W. Frick, ASPO played a key role in the landing mode decision. In early 1964, however, Joseph F. Shea left his role as Mueller's deputy for Systems Engineering to run ASPO after Frick had completed negotiations with North American for the design and manufacture of the Command and Service Module (CSM), or what was often referred to as "the Apollo Spacecraft."

Then, early in 1964, in response to direction from Shea, Grumman Aircraft Corporation, joined by North American and Charles Stark Draper's lab at MIT (guidance and navigation), created a Design Reference Mission (DRM) for Apollo in order to firm up the design requirements for the Lunar Module.[24] These requirements had been in considerable flux due to the late decision on how the overall landing mission would be conducted (Earth-orbit vs lunar-orbit rendezvous). The DRM contained President Kennedy's challenge as the first objective – that is, "Land two astronauts and scientific equipment on the near-Earth-side of the surface of the Moon and return them safely to Earth." The DRM also envisioned that the Lunar Module would be able to stay on the Moon for up to four days. With the modifications incorporated in the "Block II" Lunar Modules (LM10–12) used for Apollo 15, 16, and 17, that capability ultimately existed even though three days was the longest actual stay on the Moon in the tradeoff between science payload and stay-time.

During 1962–1964, the Space Task Group moved to Houston. This transfer was accomplished simultaneously with the completion of the Mercury Project, the initiation of the follow-on Gemini Program, and the Army Corps of Engineers' construction of the Manned Spacecraft Center on the outskirts of Houston.[25] With a permanent home for his team, Gilruth's personal system of management began to take effect. The "Gilruth system"[26] was in sharp contrast to von Braun's centralized decision-making approach (some would say "authoritarian" approach). Coordination between the Centers, however, was greatly facilitated through Holmes's Management Council that met regularly.[27] Gilruth's early technical and managerial reputation was based on innovative research as a leader in aeronautical engineering at NACA's Langley Research Center.[28] As viewed by George Low and Chris Kraft, Gilruth gradually became a leader with ideas and a sense of what would and would not work rather than a true, hands-on manager. He expected his people to do their job by "originating ideas and carrying them through to completion." The Gilruth system allowed for engineering and operational innovation to move a complex endeavor forward far more rapidly than would otherwise have been possible. If someone had a good idea, and could put together a logical set of arguments in support of that idea, it could move upward in the chain of managers irrespective of the level from which it had originated. This flexibility would disappear after Apollo, unfortunately, but it was exactly what was needed during Apollo when so much was still unknown in the universe of space engineering and lunar exploration.

A modern enterprise to Return to the Moon, fortunately, can examine the Apollo management system as well as the conceptual technical approaches that were ultimately successful. "Ultimately" is used here to emphasize that humankind twice before had attempted to put together the necessary management and technical system to land on the Moon. Simultaneously with the early years of Apollo, 1960–1968, the Soviet Union tried and failed to accomplish this goal.[29] Similarly, on January 27, 1967, the "first" attempt to move forward to that same goal by the United States also failed, ending with the Apollo 204 Command Module fire and the deaths of astronauts Gus Grissom, Ed White, and Roger Chaffee.[30]

The management lessons learned and taken to heart from the 204 fire, however – and the will to continue demonstrated by the United States Congress, President Lyndon B. Johnson, and NASA Administrator James Webb – assured that the "second" Apollo Program would succeed.

9.2.2 The fire

The uncertain nature of the Apollo enterprise and its high cost during the turbulent 1960s brought on media and political detractors. The greatest and probably only threat, however, to the continuation of Apollo prior to the success of Apollo 11 was the Congressional and press reaction to the Apollo 204 (Apollo 1) fire. The fire was extraordinarily tragic in the loss of three astronauts and in the permanent anguish it caused to so many. In a technical sense, the fire also was avoidable. In retrospect, however, this event almost certainly resulted in the changes in NASA's managerial and technical approach to Apollo that made it possible to meet the Kennedy goal within the schedule that he and Webb had originally proposed,[31] that is, ". . . in this decade . . ."[32]

The generic reason for the Apollo 204 fire is not, surprisingly, the same as that for the accidents that befell the Space Shuttles *Challenger* and *Columbia* in 1985 and 2003, respectively. Managerial discipline was insufficient to prevent the development of a safety environment in which *the abnormal became normal*. For *Challenger*, the abnormal was the design flaw that allowed repeated erosion and, in some cases, the burn-through of the primary rubber O-ring seals between sections of the solid rocket boosters used on previous flights.[33] Until *Challenger* was lost, NASA and contractor engineers thought this repeated pattern of erosion was not serious as the secondary O-ring seals always contained the burning fuel even though no erosion was contemplated in the original design.

For *Columbia*, the repeated, seemingly inconsequential loss of chunks of foam insulation coming off the Shuttle's external tank was an abnormal event that eventually was regarded as normal. Again, as nothing serious happened on successive flights, the gouging of thermal protection material also became normal. The report of the *Columbia* Accident Investigation Board describes this process in great detail.[34]

For Apollo 204, the problem lay in the repeated use of pure oxygen at greater than atmospheric pressure (16 psi) in a manned test environment, aggravated by repeated lapses in quality control in the design and manufacture of spacecraft systems, and by large quantities of flammable materials in the crew cabin. In all three cases, the absence of a technically trained and technically confident Administrator appears to have played a role. A situation was created where significant technical issues were not reported in appropriate detail to the most senior management level. This is where the buck ultimately must stop.

Although Sean O'Keefe, the Administrator in charge when *Columbia* broke apart on entry, had inherited a managerial morass from his predecessor, Daniel Goldin, he had warnings that there were generic problems with the Space Shuttle. O'Keefe had over a year to take control of this situation. In the earlier *Challenger* accident, again in a difficult managerial situation, a scientifically trained but technically and managerially inexperienced Acting Administrator, William Graham, did not take immediate control of NASA in this crisis and manage it aggressively. Responsibility for the Apollo 204 fire clearly belongs squarely at the feet of Webb, although surprising lapses in management discipline, of which he was apparently unaware, occurred in the managerial chain below him. Deputy Administrator Seamans, Associate Administrator Mueller, Manned Spacecraft Center Director Gilruth, and, most of all, Apollo Spacecraft Program Manager Shea did not perform as he might have expected.[35]

Webb, however, had designed the pre-fire reporting system that kept the Apollo 204 technical and contractor implementation deficiencies hidden. Although highly regarded as a manager, by himself and others,[36] Webb had left two essential ingredients out of his approach. He did not maintain his predecessor's system of personal oversight of technical management, and he did not build into the "Webb system" incentives for the appeal of critical decisions to a higher management authority. The Apollo Program Manager Phillips pointed out contractor deficiencies to Mueller in September 1966, but no definitive actions were taken.[37] Informal criticisms by a North American quality control inspector, Thomas R. Baron, also began to surface late in 1966 but were dismissed by North American management.[38] Also ignored, were concerns about the accumulation of hazardous material in the crew cabin that were expressed to Gilruth by Dr Charles Berry, the Center's Medical Director, three weeks prior to the fire.[39] In September 1966, the technical deficiencies leading to an unsafe spacecraft were pointed out in a letter to Shea from Hilliard Paige. Paige was one of General Electric's support team put in place by Webb to monitor the technical balance between NASA and its contractors and to provide feedback to higher management. In this case, based on his staff's apparently delayed and cursory analysis, Shea apparently ignored Paige's concerns. Paige, in turn, did not take the issue to a higher authority.[40] Thus, Webb's and North American's management oversight systems had broken down with fatal consequences to three astronauts, and potentially to the Apollo Program.

With the smoking gun of the Paige letter and the lack of action in response to it, Shea took the fall within NASA. He was transferred back to Headquarters to become Mueller's deputy, basically where he had been before 1964, and soon after left NASA to become CEO of Raytheon Corporation. George Low, who, along with Shea, had moved from Headquarters to Houston early in 1964 to serve as Gilruth's deputy,[41] immediately took a paper demotion to replace Shea as Director of the Apollo Spacecraft Program Office. Webb assumed a significant amount of Seamans' authority over organization and management activities at Headquarters and a difficult working environment developed between them.[42] Seamans finally resigned in October 1967[43] and was replaced in February 1968 by an outsider, Dr Thomas Paine, an engineer from General Electric and a former submariner.[44] In September 1967, Homer Newell had moved up to the essentially vacant Associate Administrator position, the number three spot. Strangely, other than having to tolerate much closer supervision by Webb and perfunctory oversight by the relatively passive Newell, Mueller came away from the fire incident relatively unscathed. Webb may have blamed himself more than Mueller for not forcing the latter to be more forthcoming in the years prior to the fire. He also apparently felt that Mueller was essential to the success of Apollo.[45] To help to implement his more vigorous supervision of Mueller, however, Webb brought William E. Lilly, Mueller's budget chief, into his inner circle, effectively as an Agency Comptroller.[46] Overall, in response to the fire, Webb introduced a more bureaucratic system to NASA Headquarters, a trend that to this day has never been reversed. Gilruth also weathered the storm, however, it appeared to me in 1967–1969 that Mueller, through the Apollo Program Manager Sam Phillips, might have considerably increased Headquarters' involvement in decisions related to the Center's implementation of Apollo.

On the contractor's side of the 204 fire ledger, J. Leland Atwood, North American's President, offered vigorous initial resistance to any managerial changes in his organization. Until Webb threatened to slip the Apollo schedule in order to find a new contractor, Atwood remained loyal to the management team that had built the 204 spacecraft (CSM 012). Ultimately, Atwood relented and brought in William D. Bergen, recently of the Martin Company, to replace Harrison Storms as President of the Space Division of North American. Bergen, like Low, took a paper demotion to help in the recovery from the fire. Bergen put John P. Healy in charge of managing the redesign of the Apollo Command and Service Module and Bastian Hello was assigned to run North American's facility in Florida. Healy and Hello also both came from the Martin Company.

Low sent Astronaut Frank Borman, a member of the 204 accident investigation board, to be his personal representative in the redesign and re-manufacturing effort.[47] In addition, Webb expanded the Boeing Company's Saturn booster integration contract to include spacecraft integration with the booster and thus established Boeing, reporting through Phillips, as another level of oversight over North American.

Webb atoned for some of his management failures that led to the 204 fire by nearly perfect management of the crisis it produced.[48] His rapid formation of an internal review board led by Director Floyd Thompson of Langley pre-empted any politically appointed review. With weekly Congressional and press summaries of the Thompson Board's findings, timely reorganization in response to the Board's conclusions, and managing NASA's testimony in House and Senate hearings, Webb proved to be the master orchestrator of the response to the crisis. Although wounded politically and probably psychologically, as were many others, Webb none the less was able to largely control the situation and the politics and to protect Apollo and himself. As added political cover, he also could point to, or at least hint at, the strong evidence that the Soviet Moon program was moving forward.[49] Webb's immediate response to the crisis stands in sharp contrast to the delay and lack of leadership initiative shown during a later era's *Challenger* and *Columbia* Shuttle accidents. His personal testimony to Representative Olin B. "Tiger" Teague's Space Committee on April 10, 1967,[50] was particularly telling in its definition of what was at stake in the Apollo 204 investigation, in particular, that the "Apollo bell tolls" for the nation "as well as for Grissom, White, and Chaffee."

The recovery of morale, political support and schedule after the Apollo 204 fire was complete following the nearly flawless November 9, 1967, launch of the first Saturn V three-stage rocket, fully configured and designated Apollo 4. Weighing over 6 million pounds at liftoff, with a total of 7.5 million pounds of thrust from the five F-1 first-stage engines, and a total of 11 new rocket engines that had to work, the launch also appeared to justify Mueller's insistence that von Braun implement "all up" testing rather than his traditional, methodical testing of each functioning subunit.[51] ("All-up" testing embodied the engineering and management philosophy that excellence in design, manufacturing, component and systems testing, and quality control would allow boosters and spacecraft to be tested as complete entities, therefore, shortening the overall development schedule. This philosophy, previously implemented in the Air Force's earlier intercontinental ballistic missile (ICBM) program, could be viewed as an extension of the necessary "all-up" testing implicit in the first flight of a new aircraft design.)

In Houston, during the period after the 204 fire, the leadership of George Low began to take hold,[52] and it became conceivable that we could still make the "end of the decade" schedule. The loss of confidence in Congress caused by the 204 fire, however, almost certainly contributed to reductions in post-Apollo 11 funding[53] and to post-1969 congressional reluctance to fight President Nixon's cuts of lunar exploration beyond Apollo 17. President Johnson, a lame duck throughout 1968, was unwilling to fight in Congress for a post-Apollo program due to the many other pressures of the time.[54]

9.2.3 Professional values and consequences

A traditional set of professional values drove the men and women of Apollo. These values were those of my parents and their parents; that is, traditional values developed and encouraged by their educational institutions and professional societies. The Cold War environment and the challenge given to the Apollo generation by President John Kennedy established an environment for the clear expression of these values. The core value of the Apollo generation was engineering professionalism. This intangible quality means that one personally and intuitively commits to exert his or her best efforts to the job to be done, dealing with one's peers in as honest and straightforward a manner as possible. Results rather than credit motivates action and initiative. This professionalism, remarkably widespread throughout the engineering culture of Apollo, allowed teams to form in which the capability of the whole was much greater than the sum of the individual potentials. Among these young volunteers, failure was indeed "not an option."[55]

Also paramount in the minds of the 450,000 Americans that made Apollo possible was the belief that meeting Kennedy's challenge would be the most important contribution they could make with their lives. Whether this belief turned into reality with the hindsight of 30 or 40 years is immaterial. The motivation and stamina to work 16-hour days and seemingly eight-day weeks was a primary key to Apollo's success. This is the answer to the often asked question, "If we can go to the Moon, why can't we ——?" You fill in the blank. The answer to this question is, "You can, if young men and women are as motivated as they were for Apollo."

The combination of Sputnik, Gagarin, and Kennedy created the catalyst for motivating Apollo's generation of engineers, scientists, technicians, and support personnel. Patriotism, however, sustained their dedication, as it did that of the American people and Congress. Further, seeing the astronauts walking among them along the assembly line, or working on their team to solve a problem, reinforced commitment – they knew the men whose lives depended on their skill. This created an immensely strong "customer orientation" toward country and astronauts while their teams gave them a collective experience and maturity beyond the sum of that of the individuals.

The pervasive acceptance of the values of professional engineers additionally meant that "quality" was everyone's job and not just that of a "Quality Czar." NASA's post-*Challenger* creation of such an imperial position had no long-term positive effect but instead allowed responsibility for quality to be passed up the chain of management instead of leaving it at the lower levels where it would do the most good.

Before attempting to ramp up an effort to Return to the Moon, it would be wise to understand more about what happened to NASA after Apollo. The decision to discard the Apollo capability to explore and work in deep space began before Apollo 11 had even landed at Tranquility Base in 1969. In late 1967, NASA announced that no more Saturn V boosters, Apollo spacecraft, and other related equipment would be bought beyond that necessary to support Apollo 20.[56] (No lunar missions beyond Apollo 17 actually flew. The remaining hardware was used in the Skylab and Apollo–Soyuz projects or retired to become display objects.) It would have been a tough if not impossible political fight to reverse this decision due to the aftermath of the 204 fire, the Vietnam War, other distractions facing President Johnson and later President Nixon, and the disinterest of the national media. One also sensed that the senior managers, some Center Directors, and even some astronauts, felt that they had "dodged a bullet" in not losing anyone on the trips to the Moon and that they should not keep pressing their luck.

Not making the fight to amortize the Apollo investment meant that the capabilities created by ~$110 billion (in 2005 dollars) of taxpayers' money was thrown away with hardly a whimper. In that same time frame, NASA's desire to do "new things" in engineering led its senior management to advocate to the Nixon White House the withdrawal of American astronauts to Earth orbit. Over the next few years, NASA and its Administrator, James C. Fletcher, seemed to want to build a Space Station and, if not allowed to do that, they could build the Space Shuttle that would take us to such a non-existent Space Station. This strategy to abandon the Apollo–Saturn technology base and develop an entirely new booster and spacecraft combination was finally adopted by President Nixon and the Congress in 1970.[57] At that point, NASA could not have gone back to the Apollo technology base even if it had wanted to do so. The primary "carrot" NASA offered the White House, the Department of

Defense, and the Congress to take this course consisted of a brand new, heavy lift booster and several very large, reusable spacecraft to be flown in Earth orbit only. Launches would take place every two weeks, and you would get it all for a quarter of the cost of Apollo!

Being made up of the most experienced, large space program engineering managers in the world, NASA management at the time either knew better or should have known better. If NASA's managers knew this new program was underfunded and went ahead anyway ''in order to have a manned space program,'' a very serious ethical dilemma is raised. This dilemma would reappear in NASA again and again during the next 30 years. Potentially unethical advocacy of underfunded and poorly managed new initiatives came forth in the guise of the Space Station, the X-33 single-stage-to-orbit reusable booster, the X-34 air-launched reusable booster, and even in the extended life and safety enhancements of the post-*Columbia* Space Shuttle.

Alternatively, NASA senior management and the Office of Management and Budget (OMB) really may have believed that, by dismantling much of the management system and engineering capability that succeeded for Apollo, they would have enough funding to succeed with the Space Shuttle. But consider what was eliminated:

1. Adequate funding and funding reserves.
2. Internal engineering capability and oversight of contractors.
3. Hiring of young engineers.
4. Competitive development of critical systems.
5. Strong program, financial and risk management oversight of contractors.
6. Reduction in support of space and planetary science initiatives and analysis.

''Adequate funding and funding reserves'' are fundamental to success in large, complex, advanced engineering projects. Such management reserves consist of funds necessary to handle the unknown-unknowns (or unk-unks as they are informally known in engineering jargon) inherent in research, development, and test related to ''large, complex, advanced engineering projects.'' Apollo's funding reserve was probably about 100% at the start and every bit of it eventually was needed to meet the Kennedy challenge. Without a sufficient reserve, milestones must slip to free up funds to deal with the ''unk-unk'' of the month. Repetitive slippage of milestones ultimately creates a ''milestone fence'' that cannot be breached without new appropriations from Congress. The Space Shuttle reached such a fence in about 1978.[58] At that point, the Space Shuttle was not ever going to fly without additional funding of hundreds of millions of dollars, and the Carter Administration's OMB resisted any such new appropriations. Finally, Air Force Secretary Hans Mark persuaded President Jimmy Carter that compliance with the Strategic Arms Limitation Treaty II being negotiated with the Soviet Union, much desired by Carter, could not be verified without the capabilities of the Space Shuttle. Reconnaissance satellites necessary to monitor the actions of the Soviet Union had been designed to be compatible only with being launched on the Shuttle. Once Carter understood this situation, he directed the OMB and NASA to seek supplemental appropriations for FY-1979[59] and the Space Shuttle *Columbia* eventually flew on April 12, 1981.

Unfortunately, the Carter budget supplemental could not reverse all the premature and heavily compromised engineering decisions made earlier, during design and development of the Space Shuttle.[60] In those early years, it could not be foreseen that such additional funding would become available. Engineers and managers were forced to make decisions based on the funding they had and not on what they knew they needed to minimize future risk. The life and death and programmatic consequences of those decisions became tragically obvious years later in the losses of *Challenger* and *Columbia*. Solid rocket boosters, chosen instead of the originally proposed liquid-fueled, fly-back booster, resulted in the loss of *Challenger* in January 1986. Inadequately secured foam insulation on the external fuel tank, and the lack of impact-resistant leading edge materials on the Shuttle Orbiter's wings, combined to destroy *Columbia* in February 2003.

In spite of all these and other problems, the Space Shuttle remains a tribute to the men and women of NASA and to their contractors who created a remarkable and, overall, highly successful booster and spacecraft. The Space Shuttle's deficiencies are rooted not in detailed engineering flaws but rather in political and administrative mistakes and compromises, particularly those that forced the use of solid rocket boosters during the first phase of flight and foam insulation on the external fuel tank. NASA's engineers and contractors should not be held responsible for these mistakes that reflected inadequate funding for the challenge they were given to meet. In fact, once solutions were found to the foam insulation and leading edge problems that led to the *Columbia* accident, and a full flight readiness review held, Shuttle flights should have resumed immediately rather than undertaking a nearly total tear-down and rebuilding of the remaining three spacecraft and a stand-down of Shuttle flights for well over two years. This prolonged absence of the United States from active human space flight resulted from NASA's ill-considered and precipitous commitment to do everything recommended by the accident investigation board before knowing the impact of those recommendations. More problems are potentially created than solved by this approach. Nothing in past aircraft and spacecraft operational experience in dealing with accident recovery supports this politically correct and bureaucratic path for a "return to flight."

Comparable histories of the effects of underfunding and inadequate reserves can be told about the International Space Station and the now canceled X-33, X-34, and X-48 projects, although managerial and political errors also contributed greatly to the overruns and cancellations associated with these projects. In the case of the Space Station, as with the Space Shuttle, the argument that canceling those projects would jeopardize national security and prestige carried the day when that choice had to be made. The costs, both financial and human, became far greater than if funding had been sufficient to begin with. NASA senior management, in going forward with inadequate funding, did what they believed needed to be done to survive as an agency, and they probably believed their own arguments. Indeed, once the Apollo–Saturn system was abandoned, such efforts were probably the only recourse if the United States was to remain a competitive, spacefaring nation. The ethical dilemma remains, however, and in retrospect could only have been avoided by continuing to use and enhance Apollo–Saturn capabilities and infrastructure instead of abandoning them. The budgets that were approved in the post-1970 political environment clearly could have supported such a strategy. This approach to post-Apollo space efforts would have permitted continued lunar exploration flights every two years and large Earth-orbit space stations based on Apollo–Skylab technology. In addition, the continued availability of the heavy lift capability of the Saturn V, and its decreasing cost due to long-term production contracts, would have kept other options open, including an on-call defense against Earth-impacting asteroids.

9.2.4 Internal engineering capability

NASA's internal engineering capability during Apollo was a key ingredient to success. It provided both professional contract preparation and management and internal support for evaluation of engineering proposals and the resolution of problems. It also made NASA a great place to work if you were an engineer. The erosion of a comprehensive internal design and engineering capability after Apollo made NASA increasingly dependent on the advice and interests of its contractors. While the use of modern contractors to implement large-scale engineering development projects is far preferable to the in-house, "government arsenal" approach, it can only succeed in an environment of healthy, creative tension when the customer, NASA in this case, has a fully capable and professionally current engineering staff of its own.

The lack of adequate in-house oversight expertise constitutes a recipe for disaster. As a case in point, NASA depended on its contractor for an analysis of the potential damage sustained by *Columbia* after its wing was impacted by chunks of foam insulation. That analysis was wrong but no other source of analysis was available. It led directly to an absence of a crucial sense of urgency in the early days of the flight when options for crew rescue still existed. An internal capability for such analysis would have created a constructive tension between the operational components of NASA and the contractor that very probably, based on Apollo experience, would have led to a different level of urgency and action on the part of Mission Control teams. One can never be certain of alternative outcomes; however, one can be certain that two independent and competent analytical efforts are better than one, and three are better than two.

A threat to the success of the space initiative announced in January 2004 by President George W. Bush exists in the continued absence of a strong internal engineering capability within NASA. Clearly, to be more assured of a successful outcome, that capability should be reconstituted and used as a means of attracting and hiring a large cadre of much younger engineers and scientists than exist in NASA today.

9.2.5 Competitive development of critical systems

In the early design and development phases of any large engineering project that pushes the state of the art, there will be any number of possible approaches to creating critical capabilities. The most promising of these approaches should be pursued in order to maximize the probability that the most reliable, efficient and cost-effective system is chosen in the final design. Where reasonable conceptual or engineering doubt about that final selection remains, parallel development of the best options should continue while remaining within a defined interface with other systems. In the funding environment faced after 1970, NASA found that it could not maintain this rational approach or could not maintain it beyond the Space Shuttle's earliest design activity. Many early design decisions had to be made in highly challenging technical areas involving the development and manufacture of the first reusable, winged spacecraft, and a very large spacecraft at that. Critical new areas included the solid rocket boosters, the Shuttle main engines, the thermal protection system, structural materials, onboard computers, crew rescue, and many more. The financial, operational, and human costs of premature design decisions would be evident later, with tragic consequences. In strictly financial terms, the cost has been far greater than would have been the case if the required resources had been provided at the proper time.

9.2.6 Value of youth

The enthusiasm, imagination, and stamina of young men and women formed the heart and soul of Apollo. Combined with their unfamiliarity with failure, they carried Apollo to the Moon and back as they have always underpinned the United States from the Revolutionary War to the War on Terror. Without these dedicated young people, no great milestone of American freedom would have been reached or will be reached in the future.

Underfunding of Space Shuttle development and subsequent projects attempted by NASA, combined with civil service rules concerning employee tenure, prevented the continual rejuvenation of its employee base. In contrast to the early years of Apollo, the average age of employees began to increase year by year. There was a commensurate and natural decrease in the level of imagination and energy of the Agency, along with the departure of many top engineers and managers to other government agencies and the private and academic sectors. At times, particularly in the 1990s, funding restrictions resulted in formal reductions in force (RIFs), carried out without attention to the mix of skills needed to maintain quality performance. Such RIFs and normal attrition without new hiring authority increased dependence on support contractors as well as the major project prime contractors.

These personnel-related matters, along with the *Challenger* and *Columbia* accidents and the erratic and self-centered personalities of some senior managers,[61] produced a serious deterioration in Agency morale in the late 1980s, 1990s, and early 2000s. Clearly, a Return to the Moon initiative for NASA, in itself, has helped to restore morale. The embedded personnel and management issues, however, that helped to create the post-Apollo problems also need to be addressed, quite possibly through special legislation to modify existing civil service rules as applied to NASA.

9.2.7 Management oversight

Even before the Apollo 204 fire, and particularly after that tragic wake-up call, the system of programmatic, financial, and risk management that NASA Administrators Glennan and Webb had devised matured rapidly. Coordinated program plans existed and management reviewed internal and contractor performance against those plans. Financial plans, reviewed frequently with the OMB and the relevant committees of Congress, were monitored closely, and they contained sufficient financial reserves and congressional support to solve critical issues as they arose. And throughout the Agency, programmatic, financial, and technical risks were identified, reviewed, and revised with specific plans and actions taken to minimize those risks. No management is perfect, but after the 204 fire, Apollo management showed the toughness, discipline, competence, and flexibility to come very close.

Unfortunately, in the midst of all its other post-Apollo problems, NASA began to lose its commitment to and its capability for strong program, financial, and risk management of its contractors as well as its internal activities. Contracts were signed and invoices paid without this controlling discipline for monitoring performance. As a consequence, large delays and cost overruns began to surprise managers of essentially all major programs. From the Space Shuttle to the International Space Station (ISS), management problems occurred repeatedly. To complicate the ISS situation further, political decisions by the Clinton Administration put Russia's technical and funding decisions in the critical path to successful implementation. Development of the X-33 single-stage-to-orbit launch vehicle became so costly and chaotic that even NASA realized it had to be canceled. The X-34 unmanned air-launched reusable booster also was canceled as collateral damage tied to the X-33 decision. With the X-34, however, the contractor had met its obligation to build the airframe and control systems, but NASA's Marshall Space Flight Center was unable to deliver a rocket engine after four years of internal development effort – another lesson in the deterioration of NASA's internal engineering capability.

For a significant probability to exist that NASA can implement the Exploration Initiative set forth by President Bush, its management systems must be repaired and modernized. A private initiative to Return to the Moon has no less an obligation to create strong management systems and management culture (see Chapter 11).

9.2.8 Political support

Political support for a national Return to the Moon effort will be critical whether led by NASA or by a private initiative, although much more so for NASA. Such support by Congress and the electorate must sustain NASA's funding over many changes of Administration and potential changes in the political control of one or both houses of Congress. A private initiative will need at least passive political support and ideally active support and advocacy in the face of regulatory, tort, and international challenges if they should occur.

The Apollo 204 fire initiated the slow waning of Kennedy inspired political support for NASA; however, it remained strong enough to give Apollo a remarkable place in human history as well as in exploration and science. After the goal of landing on the Moon was achieved in 1969, general media interest largely disappeared, only to be revived briefly by the suspense accompanying the rescue of Apollo 13. As media interest waned, so did broad congressional interest, to be replaced by locally based advocacy by those House and Senate members who had constituent interests in NASA centers or in its contractor employment. This local interest has sustained NASA but has had one adverse effect – enough political clout exists to prevent a reduction in unneeded infrastructure. As a consequence, NASA maintains essentially the same facilities as were needed for Apollo with less funding in real dollars and less efficient management. For the foreseeable future, as for the decade of the 1990s, NASA can expect funding near its current levels and should plan its program and financial management accordingly. Whether this funding level and NASA's management can sustain the Exploration Initiative remains to be seen. Competent management must understand that Congress will probably maintain NASA's historically constant funding level and plan to avoid funding peaks. Unless NASA becomes more efficient as an organization, this will be a difficult order to fill.

The shift from national to local political interest paralleled the loss of media interest in NASA's successes and a concentration on its failures and problems. Vietnam, Watergate, the continuing Cold War, and now the War on Terror and celebrity criminal trials further occupy media and political attention. On the budgetary side, political emphasis has shifted to entitlements, making the funding of routine but discretionary space activities a much more difficult sale in the political marketplace. Indeed, the long-term, unfunded liabilities inherent in retirement, medical, and housing entitlements, as well as demands for refurbishment and expansion of the nation's transportation infrastructure, will continue to reduce discretionary spending on space as a proportion of non-defense federal budgets. For the foreseeable future, new space initiatives by NASA will be significantly underfunded unless heroically managed, or unless a political environment comparable to that faced by President Kennedy should reappear and be sustained.

With President Kennedy's death in 1963, almost six years before the goal of a Moon landing was reached, White House leadership of Apollo and the nation's future in space became increasingly distracted. The

Johnson Administration kept the main thrust of Apollo on track, but after the 204 fire in 1967, and with the continued trauma of the Vietnam War, long-term interest in space disappeared. Vietnam and the Watergate scandal clearly distracted Presidents Nixon and Ford and their advisers. For Nixon, the fact that Apollo was associated with Kennedy probably reduced his enthusiasm for continuation of flights to the Moon any longer than it could serve as a political plus. Cancellation of Apollos 18–20 occurred during his first Administration. In fact, the final flight to the Moon, Apollo 17, originally scheduled for launch in July 1972, was nearly cancelled to avoid the possibility of an accident affecting Nixon's re-election campaign.[62] A compromise engineered by George Low slipped Apollo 17's launch from July to December, allowing the mission to proceed.

President Jimmy Carter apparently had little interest in space policy unless it affected one of his personal priorities. As discussed above, he agreed to complete development of the Space Shuttle only when it was clear that it would be needed to launch intelligence satellites necessary to monitor Soviet compliance with arms limitation treaties he favored. For President Ronald Reagan, the Cold War and his Strategic Defense Initiative (SDI) overshadowed space, although Reagan did formally initiate the Space Station program. Unfortunately, the consequences of the deterioration in NASA's management skills were not considered in making this decision.

President George H. W. Bush made an attempt to rejuvenate the vision of human permanence in deep space with his Space Exploration Initiative (SEI) in 1989. While conceptually sound, SEI was lost to poor salesmanship on the part of both the White House and NASA and increasingly aggressive partisanship by Congressional and Senate Democrats. The initiative immediately became tagged with a specious $400 billion cost estimate – a political showstopper. SEI should have been debated in the broad context of national policy under the assumption that it would be supported by an indefinite commitment to sustainable annual funding. The Bush 41 White House also made the mistake, in 1992, of selecting a poor manager and leader as NASA Administrator who presided over the next 10 years of badly managed programs, political meddling, and personnel downsizing, including eight years under the Bill Clinton Administration.

It is not yet clear whether the White House of President George W. Bush (Bush 43) yet recognizes the depth of its managerial problems in NASA. The selection of an experienced and knowledgeable engineering manager as the new Administrator of NASA, Dr Michael Griffin, certainly represents an excellent first step. It also is not yet clear, in view of all the other issues competing for attention, whether the White House is willing to spend the political capital necessary to build political momentum for the new Exploration Initiative – that is, momentum that can be sustained from Administration to Administration and Congress to Congress. On the positive side, President Bush has made it clear that the Exploration Initiative has an indefinite lifetime and requires steady annual appropriations and managerial focus.

9.3 ESSENTIAL CONDITIONS FOR SUCCESS

What became the Apollo Program with President Kennedy's announcement on May 25, 1961, represented the culmination of studies and design activities that had begun during the second Eisenhower Administration and the first few months of the Kennedy Administration.[63] These efforts were a considered response to the very visible accomplishments of the then Soviet Union in booster development and space flight, demonstrated by the launch of Sputnik I in October 1957 and intelligence estimates of Soviet progress in intercontinental ballistic missiles. In this Cold War environment two critical activities were initiated. First, in addition to the Mercury Program to put Americans into Earth orbit, in 1958–1960 NASA began studies of human space flight to the Moon, largely under the leadership of George M. Low.[64] Second, in January 1960, Eisenhower personally directed NASA to accelerate the development of what became the Saturn V class of heavy lift boosters, an endeavor he had already encouraged repeatedly.[65] Eisenhower also responded to Sputnik by funding major advancements in the country's educational system. The latter two efforts were an intriguing contrast to Eisenhower's several public expressions of disinterest in human flight to the Moon. At that time, for example, a booster of the Saturn V's capability could have had no other obvious purpose but to send men to the Moon.

Public concern was further increased by Kennedy's 1960 campaign allegations of a "missile gap" relative to the capabilities of the United States versus those of the Soviet Union. From a literal national security perspective, this alleged adverse missile gap did not exist. Only four months after taking office, however, President Kennedy was faced with a real "gap" in US space flight capabilities when, on April 12, 1961, the Soviet Union put Yuri Gagarin into orbit around the Earth. This catalytic event immediately focused the attention of Kennedy and his advisers on space. Once assured that the earlier NASA studies showed that a landing on the Moon was feasible and that it was also feasible to build a Saturn V class booster, Kennedy put his presidency and personal energy behind Apollo.[66]

Before personnel and an organizational structure could be put in place to manage Apollo successfully, a number of other necessary conditions needed to exist. On the one hand, the overall technological and managerial base of the country needed to be adequate to the task. This was the case, thanks to the post-World War II demands for continuously more capable missile, aerospace, and computational systems. Although technologies needed to be enhanced and systems engineering needed new approaches, little if any new component technology was required. Further, the potential had to exist for tough, competent, and disciplined senior management to step forward.[67] The source of such management for Apollo lay in the personnel inherited from NASA's precursor agency, the National Advisory Committee on Aeronautics, later from the British–Canadian A.V. Roe Corporation, and finally from the Army Ballistic Missile Agency.[68] Importantly, a sufficient reservoir of engineers in their twenties, and experienced aerospace engineering managers in their thirties and forties, was available. Because of the emotional and educational response to Sputnik I by thousands of Homer Hickums,[69] renewal of this reservoir of talent, imagination, energy, and endurance continued for many years.

In summary, the six basic conditions for Americans to achieve "great engineering goals" like landing on the Moon are as follows:

1. An achievable goal based on an adequate base of technology.
2. A potential for tough, competent, and disciplined management.
3. A sufficient reservoir of young engineers and engineering managers to implement program plans.
4. An environment of national unease.
5. A catalytic event or a suddenly obvious threat that stirs public emotions.
6. An articulate and trusted national leader.

In one way or another, these basic conditions existed prior to all great historical endeavors undertaken by the American people where engineering constituted the critical component of success. These endeavors range from the winning of major wars, to the construction of the Panama Canal, to the building of transcontinental railroads, to the development of a nuclear-powered Navy. Clearly, the same conditions will be required for a successful return to the Moon, whether by government or by private entrepreneurs.

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10

NASA: RESTRUCTURING FOR DEEP SPACE

PRESIDENT George W. Bush has challenged the United States to Return to the Moon and go to Mars and beyond through his Exploration Initiative for NASA.[1] Fast-forwarding about 30 years from Apollo to the present, where does NASA stand today with respect to conducting major projects in deep space? With President Bush's election to his first term as President of the United States and before he articulated the new Initiative in January 2004, I volunteered a number of suggestions as to how NASA could be revitalized to potentially undertake Apollo-scale activities once again. Others have echoed these suggestions over the last few years.[2] That advice was contained in several e-mails I sent to White House staff and the Director of the Office of Management and Budget. Slightly edited and annotated (text contained in brackets []) for clarity, those communications are given in Sections 10.1–10.9 below. These submissions provide a snapshot of how NASA appeared to me and many other outside observers at the turn of the twenty-first century, and what was needed for rebuilding and focusing that storied agency. NASA's newest Administrator, Dr Michael Griffin, has begun to address these concerns.

10.1 NASA IN POLITICAL TERMS

May 9, 2001 – E-mail to John Bridgeland, Director of the Domestic Policy Council, and Joel Kaplan, Special Assistant to the President in the Office of the Chief of Staff, and on May 10, 2004, copy to Mitch Daniels, Director, Office of Management and Budget, elected Governor of Indiana in 2004. (These points also were discussed in a March 22, 2001, phone conversation with Karl Rove, Adviser to the President, and an April 11, 2001, phone conversation with Ken Mehlman, White House Political Director and later Campaign Manager of the President's successful 2004 re-election effort. These communications should be viewed in the context that the Space Shuttle *Columbia* disintegrated over Texas about 11 months later and that President Bush announced his Moon–Mars Initiative 22 months later.)

> As I have previously discussed with both of you [by phone] some of the issues related to NASA, I am addressing this new correspondence to you jointly. I hope my thoughts will be helpful to you both.
>
> I have become increasingly concerned that political risks for the President related to NASA's activities are rising rapidly. His success on many other fronts is too important to the Nation's future to take any unnecessary risks related to what now may [be] considered background noise, given all your other challenges. After a successful re-election in 2004, an initiative related to the Moon and Mars may have a great deal to do with how this Presidency is viewed by history.
>
> The President's immediate exposure relative to NASA appears greatest in four areas:
>
> First of all, in addition to being an avoidable tragedy, a Space Shuttle accident due to the poor management by Headquarters that has led to an over-extended Shuttle workforce at the Kennedy Space Center would cause a major distraction in implementation of the President's national agenda. One only need remember the *Challenger* accident in 1986 to understand the consequences. Many indicators strongly suggest that this risk is increasing every day. In the near-term, the risk of a Shuttle accident due to personnel problems can be managed by temporarily re-assigning appropriately skilled personnel from other NASA Centers and contractors. Longer term, NASA must rebuild its senior management team with experienced managers and its

skill base with young engineers and scientists. [The *Columbia* accident occurred on February 1, 2002, almost nine months after these concerns were first raised.]

Secondly, NASA management has not properly addressed the problems of Russia's controlling role in the International Space Station program, currently demonstrated by the ludicrous situation of having an untrained tourist wandering around the Station in the midst of major construction and operational problems. Tourism, although hardly a major issue compared to the Space Station budget problems, can be very important in the future and NASA should be thought of as an enabler. If nothing else, tourism clearly has caught the attention of the press. Unfortunately, NASA's recent pronouncements [questioning Russia's initiative] are now looked at as sour grapes. Under the previous Administration, NASA and State negotiated some poor and probably unnecessary agreements with Russia. Those agreements clearly need to be revisited in light of other foreign policy issues, however, for now Russia's actions appear to be consistent with the letter of those agreements if not their spirit. [Dependence on Russia to supply and crew the Space Station became total with the Shuttle launch stand-down after the *Columbia* accident.]

Thirdly, NASA management is committing the US to international agreements that would ultimately increase Russia's leverage over operation of the Space Station rather than reduce it. There is an option for eliminating this leverage by creating a "kit" for the US Space Shuttle payload bay that would permit extended Shuttle stays at the Station, possibly for up to three months. These extended duration Space Shuttles would provide for all the capabilities NASA has given up in the face of the $4 billion or more of overruns just recently identified for still unexplained reasons [and unexplained still in 2005]. Specifically, a Shuttle docked at the Station provides:

(1) extra habitat for more than the current three personnel and which are required for full scientific utilization of the Station (a capability lost with the cancellation of the US Habitat Module[3] and a significant issue with many in Congress and in the scientific community),
(2) orbital reboost of the Station to account for the slow decay of near-Earth orbits due to atmospheric drag (a capability lost with the cancellation of the US Propulsion Module[4] and which must be provided by Russian Progress supply vehicles when no Shuttle [is] available),
(3) full crew return in the event of an emergency on board the Station (a capability lost with the cancellation of the US Crew Return Vehicle[5] which leaves emergency return dependent on having the three person Russian Soyuz capsule docked with the Station), and
(4) resupply of Station consumables (now dependent on the Russian Progress vehicles between Shuttle visits).

Fourthly, personnel decisions relative to senior staff appointments are being made by the current [lame duck] management that may make it even more difficult to build a quality management team to support Administration initiatives in the future. [Administrator Daniel Goldin was replaced by Sean O'Keefe, Deputy Director of OMB, in 2002.]

These four vulnerabilities are just the tip of the iceberg. For example, any Presidential initiative in 2004 or beyond will be dependent on rebuilding NASA's management team with high quality line managers having both corporate and federal management experience and on replacing skills and youth lost to a poorly managed 26% down-sizing since 1993 and another 25% retirement wedge.

[President Bush announced a major Moon–Mars Exploration Initiative on January 14, 2004.]

May 29, 2001 – E-mail to Mitch Daniels:

With respect to the risk of a Space Shuttle launch accident, it would seem advisable, in the absence of a new NASA Administrator, that the OMB order a "delta" flight readiness review (FRR)[6] *before too many more Space Shuttle launches occur, the next now scheduled for about June 20 of this year* [emphasis added]. This review should be completed in a few weeks time (it certainly should not be allowed to drag on for more than a month). You may want to wait until a new NASA Administrator is named who, although he or she would not have been confirmed, might have some thoughts about the make-up and charter of the review team. I would think that the delta FRR should be conducted by a "blue-ribbon" team of three to six experienced manager/engineers from industry and government and not currently employed by NASA or a NASA contractor.

The review should begin with separate meetings between the review team and the following groups: (1) Flight crews from the up-coming three missions and those of the last six missions; (2) line managers of the Kennedy Space Center shuttle processing and launch teams; (3) line managers of the USA [NASA prime contractor] shuttle processing team; (4) a representative group of processing and launch technicians; (5) flight directors and flight controllers for the next three missions and the last six missions; (6) line managers from the booster design and refurbishment teams at Marshall Space Flight Center; (7) Shuttle systems project managers from the Johnson Space Center; (8) simulation and training teams assigned to the next three and the preceding six missions; (9) relevant quality control and assurance personnel; and (10) other individuals or groups that are identified as having relevant knowledge of the current status of Shuttle systems, operations, training and risks related thereto. In the course of these meetings, information on any and all hardware, software, and processing anomalies related to the last three years for Shuttle flight and test activity, and the status of actions taken on such anomalies, should be obtained, reviewed and discussed with the individuals responsible for identifying, tracking and resolving the anomalies.

OMB's charter to the review team should be to penetrate as close to the working level of shuttle operations as necessary to identify any potential safety of flight or reliability issues and that current NASA and United Space Alliance (the Shuttle processing contractor) should facilitate the team's effort. Hopefully, the team's work and report will be complete about the time a new Administrator is confirmed by the Senate. The result of this delta-FRR, hopefully, will confirm that the next Shuttle mission is ready to go at minimum reasonable risk with a minimum impact on the near-term flight schedule. If the review, however, *identifies unacceptable risks due to unresolved technical anomalies that relate to the safety of flight of all Shuttles* [emphasis added], then a delay to fix those anomalies clearly would be required unless some compensating urgency has developed relative one of the Shuttles' planned missions and that urgency warrants the extra identified risk.

If the review determines that an unacceptable risk exists with respect to only one of the four Shuttles, NASA would be required to undertake a rescheduling of that vehicle until the risk can be mitigated. If the review determines that risks to all Shuttle operations are growing as a consequence of a lack of sufficient skilled personnel in one or more areas of activity, NASA should be required to identify comparably skilled personnel at the various NASA Centers, at NASA contractors, and/or who are former NASA employees, and to take steps necessary to bring such additional skilled personnel to the point-of-need on a temporary basis.

Longer term, NASA must rebuild its senior management team with experienced line managers and its skill base with young engineers and scientists. If the review determines that the Shuttle fleet requires accelerated refurbishment and safety modifications, then the release of funding for these planned activities also should be accelerated. We now are at a point, however, with the Space Station in orbit and permanently occupied by multinational crews, where a long-term stand-down of the Shuttle fleet cannot be sustained as it was after the *Challenger* accident. *In the case of another accident, we must be prepared to move quickly to fix what can be fixed but to then launch again based on a risk analysis of the next Shuttle in line even if a full, traditional accident investigation has not been completed* [emphasis added]. This is normal philosophy in the aircraft business and, by default, must become the normal philosophy in the space launch business. Continuing refurbishments and improvements to the Shuttle fleet should be made with this new philosophy in mind.

[The loss of the Space Shuttle *Columbia* on February 1, 2003, prompted a prolonged stand-down in launches of more than two years. Of course, there was no guarantee that the suggested delta FRR would have disclosed the vulnerability of the Shuttle's wing to the impact of foam shed from the external fuel tank. Foam shedding was a **known anomaly,**[7] however, and the probability is high that the issue would have come to the review team's attention.]

10.2 MANAGEMENT RESTRUCTURING

May 13, 2001 – E-mail to Mitch Daniels:

> Many of NASA's current difficulties are a direct consequence of the management structure and personnel now in place, as is implicit in Sean O'Keefe's May 3, 2001, testimony for OMB before the VA/HUD Appropriations Subcommittee of the House. [O'Keefe served as Deputy Director of the OMB and had not been named NASA Administrator at the time.] One obvious indication of the problems of management structure is the organization chart on NASA's web page – it shows that all 22 senior managers report to the Administrator. Apparently, each of the NASA Center directors also report directly to the Administrator, in fact if not by published reporting lines. It is hard to imagine that such a structure would provide a coherent decision-making environment. Recent difficulties in NASA's cost management, project execution, and Center guidance would appear to confirm that assessment.
>
> My recent look at this situation indicates that a structure taken from successful corporate experience would better meet NASA's needs now and in the future. This would be particularly true if the President should decide to propose a major new space initiative within his first term. I have summarized this approach below and attached a suggested organization chart.
>
> In the largest context, NASA is a corporate subsidiary of the Administration of which the President is the obvious Chairman and CEO. The "parent" corporation's Board of Directors is made up of those on the White House staff that implement the President's directions, particularly the OMB, on a routine basis.
>
> In this corporate analogy, the Congress provides the broad regulatory control experienced in the private sector in the form of the SEC, FTC, etc.
>
> It would appear, then, that NASA, as a subsidiary of the Administration, would benefit from the following "corporate" structure [see Figure 10.1]:
>
> *Chairman* – the Administrator (with both corporate director and federal management experience)
>
> *CEO* – the Deputy Administrator (with both corporate line management and federal management experience)
>
> *NASA's "Corporate Board"* would consist of a reconstituted Advisory Council with the Aerospace Safety Advisory Board as a "Board" committee along with the formation of an Audit and Finance Committee. The function of Independent Auditor would be filled by the NASA Inspector General, as it is today, and possibly by the use of an independent private sector firm.
>
> The next level of management reporting to the Chairman and CEO would be limited to the following six line managers. Extensive experience in or demonstrated talent for line management should be mandatory in each of these six positions.

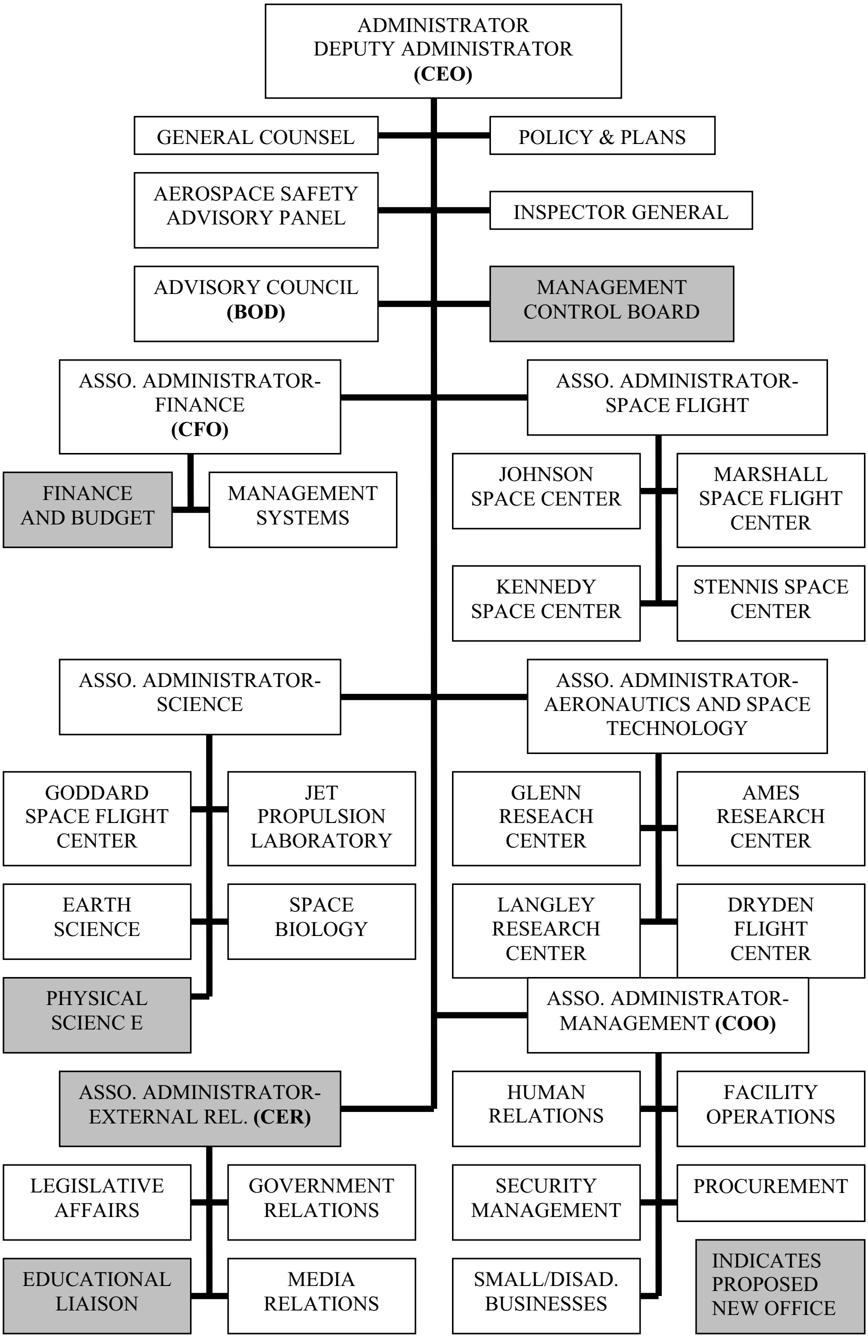

FIGURE 10.1 Suggested NASA organization 3/2/2001.

CFO – the finance and budget director with responsibility for various related functions, including management systems (IT) – [both] private sector and federal financial management experience extremely desirable.

COO – the internal functions manager for day-to-day NASA Headquarters and Centers' Support – [both] private sector and federal operations management experience extremely desirable.

CER – the external relations manager, including legislative affairs public affairs, interagency coordination, etc. – [both] private sector and federal external relations management experience extremely desirable.

Office of Space Flight – (the present Code M) the program manager for human space flight activities including direct management of the four related Centers, Johnson, Marshall, Stennis, and Kennedy (ISS program management probably should stay at this level with Project management set up at Johnson) – [it may be a] tough job to find the right mix of experience and talent but there are several very good possibilities if they can be persuaded to join up.

Office of Science – (the present Code S) the program manager for science activities including the direct management of two related Centers, Goddard and JPL – needs a respected scientist-manager, who also will be tough to find but with some good possibilities out there.

Office of Aeronautics and Space Technology – (the present Code R) the program manager for advanced aeronautical and space research and technology development activities, including direct management of four related Centers, Langley, Glenn, Ames and Dryden – needs a quality engineering manager with the vision to see where technology advancements beyond the current reach of industry will pay off in the future.

Some complexities in the division of management responsibility between Codes M, S, and R have developed that will need to be straightened out. In general, however, the above arrangement should work and will allow stronger management control (given the right people in the top eight slots) and a reduction in overhead costs related to Center operations. The major Centers, to greater or lesser degree, have become miniature NASAs and need a much clearer definition of their roles and missions. None probably need to be closed – among other things, this would be an unnecessary battle with states that largely supported the President.

[Significant simplification of NASA's organizational structure occurred in 2004. Time will tell if the right senior managers are in place to carry out the President's Moon–Mars Exploration Initiative.]

There also may be merit in looking at operating the Space Shuttle and the International Space Station (ISS) as "wholly owned subsidiaries" of NASA with their own Boards, chaired by the NASA Administrator and having both government and private sector Directors. The ISS Subsidiary would contract at arms length with other NASA entities, the Shuttle Subsidiary, other governments, and the private sector for needed services. Conversely, customers for ISS applications, such as science, biomedicine, tourism, etc., would contract with the Subsidiary for its services (probably on an auction basis initially). As you know, the "ISS Subsidiary" already has Russia as a 30% "equity" owner for better or worse. (That degree of dependency obviously needs to be re-examined, but that is a separate issue.) This subsidiary approach to ISS and Space Shuttle management would allow a phased examination of the feasibility and financial viability of privatizing the Space Shuttle and/or the ISS.

10.3 CENTERS' ROLES AND MISSIONS

June 8, 2001 – To Mitch Daniels:

The ten NASA Centers constitute the inherent strength of the Agency as well as one of its greatest management challenges. When staffed with young, highly motivated engineers, scientists, and managers, and when assigned well-defined and historically relevant roles and missions, the Centers truly can be a unique national resource of still untapped potential.

One of NASA's imbedded basic financial burdens, however, is carrying a Center-based infrastructure created in large part over 30 years ago to support a $30–35 billion annual expenditure [in 2001 dollars] during Apollo as compared to a $14 billion budget today. [In 2005 dollars, these numbers would be approximately $40–48 billion and $16 billion, respectively.] Closing one or more Centers could, in theory, solve this problem of excess facility overhead. Politically, however, Center closures probably are non-starters as most are in states that have been very supportive of the President, i.e., Texas, Alabama, Mississippi, Florida, Virginia, and Ohio. (Three are in California [and one in Maryland].) Further, if the President decides on a major new civil space initiative during his tenure, the existing facilities and more may be needed for implementation.

Additionally, with inappropriately overlapping and historically conflicting roles and missions, and less than optimum program and financial management systems, most of the Centers currently operate inefficiently and well below their individual and collective potential. Critical Center infrastructures also are in need of extensive refurbishment while others may need to be mothballed or put to non-NASA use, at least temporarily. Innovative approaches to funding refurbishment and to rationalizing infrastructure are long overdue.

Steps to restructure the Centers' roles and missions of course must be considered in the light of local political interests as well as on purely managerial grounds. Cognizant Senators, Congressmen, Governors, and local elected officials have understandable interests in the potential impacts of changes at the Centers nearest them, interests that must be factored into any proposed realignments of roles and missions. This is a nice way of saying that politicians resist losing what they perceive is legitimate "pork."

Political persuasion for change would be most easily undertaken in the context of a major Presidential initiative that "lifts all boats", i.e., that requires the expansion of each Center's technical and managerial activities. The present situation, however, is not yet conducive to a major Presidential initiative. It is, rather, one that requires a rejuvenation of NASA's management foundations so as to both properly conduct its current assignments and to be prepared for any initiative the President may ultimately put forth. Political interests must be convinced that improved program and financial management at the Centers will be of net benefit to the local economies and is a necessary condition to future growth.

With the above in mind, a recommended preliminary delineation of the NASA Centers' most logical roles and missions follows:

1. *Kennedy Space Center* (KSC), Florida – (a) launch operations, (b) Space Shuttle launch and recovery operations, (c) launch safety research and technology development, (d) Space Shuttle maintenance and refurbishment, (e) International Space Station pre-launch integrated testing.

2. *Marshall Space Flight Center* (MSFC), Alabama – (a) heavy lift propulsion research, technology development, and test, (b) large mass interplanetary propulsion technology, (c) Space Shuttle propulsion systems oversight, upgrades, and maintenance, (d) reusable launch research and technology development. (MSFC appears to have major problems in how it manages new programs as indicated by the X-33 and X-34 situations. This will be a major challenge for the next leadership team in NASA. Also, MSFC has worked some large astronomy spacecraft, i.e., Hubble and Chandra and microgravity research. Whether these should remain areas of MSFC responsibility or be transferred to more appropriate Centers would depend on an overall review of the details of roles and missions.)

3. *Stennis Space Center* (SSC), Mississippi – propulsion test activities. (Stennis currently has responsibility for "commercial remote sensing" activities that involve NASA. This would be more appropriately placed at Goddard Space Flight Center as indicated below.)

4. *Johnson Space Center* (JSC), Texas – (a) human space flight planning, development and operations, (b) human space flight research and technology development, (c) human space flight operations research and technology development, (d) Space Shuttle systems oversight and upgrades, (e) International Space Station systems oversight, upgrades, and maintenance, (f) extraterrestrial sample curation and distribution. (Space biomedicine should not be a major responsibility of JSC as it is now, except for the normal medical surveillance of the astronauts. The relative lack of progress in this field is partially due to JSC's managerial control over it. I will make separate suggestions on how space biomedical

research might be handled in a separate NASA Situation e-mail [see Section 10.8].)

5. *Langley Research Center* (LRC), Virginia (strong academic and industrial associations assumed) – (a) broad aeronautical research and technology development and related systems engineering, structures and materials, airframes, and atmospheric sciences (b) preliminary design of space and launch systems.
6. *Glenn Research Center* (GRC), Ohio (strong academic and industrial associations assumed) – (a) aerospace-related research and technology development in aero-propulsion (particularly small masses), (b) research and technology development in energy production and conversion systems, energy conservation, robotics, and materials. (If it ever appeared appropriate for NASA to undertake broader responsibilities for transportation research and technology development, GRC would be the logical focus of that work. It might include (1) the application of aeronautical and information technology to very high speed magnetic levitated ground transportation and (2) the application of space fusion power to air and sea craft propulsion. GRC also would be the logical center of research and technology development of extraterrestrial mining and materials processing.)
7. *Ames Research Center* (ARC), California (strong academic and industrial associations assumed) – (a) advanced and fault tolerant computing, software, and information management, (b) space and aviation human factors, (c) aeronautical research and technology development in operational procedures and air transportation management, (d) astrobiology research.
8. *Goddard Space Flight Center* (GSFC), Maryland (strong academic and industrial associations assumed) – (a) communications research and technology development, (b) Earth and space science research, (c) Earth and space science sensors research and technology development, (d) space astronomy research and technology development, (e) design, production, test, launch, flight operations, and data analysis related to specific space and earth science projects.
9. *Dryden Flight Research Center* (DFRC), California – (a) aeronautical flight test services, (b) aeronautical and atmospheric flight research.
10. *Jet Propulsion Laboratory* (strong Caltech and other academic associations assumed) – (a) planetary sciences missions management, (b) planetary and astronomical sensors research and technology development, (c) design, production, test, launch, flight operations, and data analysis related to specific planetary science projects. (JPL is different than other NASA Centers in that it is managed through a contract with Caltech. Caltech's appointment of a new Director for JPL soon after the President's election

presumably without consultation with the Transition team suggests the need for stronger consultation between Caltech and NASA's future leadership. Like MSFC, JPL has shown problems in project management in recent years. New management and competition with other comparable entities, such as, the Applied Physics Laboratory at Hopkins, may improve its performance.)

11. *Headquarters* – (a) program management, (b) budget coordination and advocacy, (c) educational activity coordination, (d) public relations coordination, (e) interagency and international relations coordination, (f) space law development and coordination, (g) privatization initiatives, (h) advisory committee management, (i) human resources coordination, (j) legal counsel coordination, (k) intellectual property management and technology transfer coordination, (l) future initiative planning and preliminary design, and (m) provision for operational support of the Agency and its Centers.

There are many second level details that will be pertinent to a rationalization of Centers roles and missions. For example, where projects require cooperation and coordination between one or more Centers, clear definition of responsibilities, expected performance, and managerial control are required. Further, in addition to their individually assigned roles and missions, each Center also would need to undertake local educational and technology transfer initiatives under the general oversight of Headquarters.

If a tightening of roles and missions is possible, and if improved project and contractor management can be achieved, then additional resources will be available internally for other NASA activities, such as, increased parallel design engineering on approved missions, technology transfer, and definition of future initiatives that may be required by the President.

10.4 LONG DURATION SPACE SHUTTLE

May 21, 2001 – To Mitch Daniels:

The necessary decisions in response to budgetary problems facing the International Space Station, of course, have the additional consequence of increasing our dependence on Russia for emergency crew return, for reboost, and potentially for habitation sufficient to conduct meaningful scientific research. As the recent Russian sponsored tourist visit to the Station indicates, they have significant leverage related to other Station activities as well. For example, you may not be aware that one-half of the training time of our Station crews must be spent in Russia whether needed or not, representing both an added cost to NASA and a burden on families. This leverage is the result of the language negotiated in agreements signed during the last Administration.

There are a number of piecemeal ways by which some of Russia's control and its indirect costs might be reduced, however, none of them appear very attractive and all will cost money and time and may require further loss of operational control over the Station's destiny. NASA's recent tentative agreement with Italy on a possible alternative habitation module, and its approach to Europe for supplying an alternative crew return vehicle (CRV), are current examples of this problem. On the other hand, use of available funds for the development of a payload bay "kit" for the Space Shuttle that would allow it to stay docked with the Station for up to 90 days would reduce the Russian leverage to whatever level we wish it to be, including zero. A docked, Long Duration Shuttle would provide for emergency crew return, necessary reboost of the Station, and habitat for as many as five additional researchers until such time as the technical and political issues raised by long-term alternatives can be fully evaluated.

The concept of an extended orbital capability for the Space Shuttle was studied formally by NASA in the late 1980s. To quote my former NASA colleague Arnold Aldrich, the Space Shuttle Program Director at the time, "The space shuttle orbiter prime contractor, Rockwell International, was able to readily define mission extension modifications, which could support 30- and 60-day-on-orbit stay times, and it appeared that a capability for up to 90 days might well be achievable." (*Space News Letters*, April 30, 2001, p. 14, responding to former astronaut Owen Garriott's commentary on the same subject in the April 9th issue.) Several other engineers who were active during this period have made similar comments to me personally over the last several months as I have investigated this problem of Russian leverage and lack of crew time for Station science.

A Long Duration Shuttle also would permit a reactivation of NASA's original professional-in-space initiative of which the Teacher-in-Space selection in 1984 was the first. A well-thought out "paying tourist" initiative in combination with a commercially developed habitat module might even grow out of this effort as might other potential commercial initiatives.

A careful review of (1) the international agreements that affect Space Station construction and operations, (2) the near and long-term nature of the relationships we wish to have with Russia, and (3) the value of research in and other applications of this laboratory in space is clearly in order. Independently of such a review, however, a rapid re-evaluation of the feasibility and cost of developing a kit to provide for up to 90 days on orbit for the Shuttle also would seem to be warranted.

[In 2004, the extended impact of the loss of the Space Shuttle *Columbia* and the planned retirement of the remaining Space Shuttles around 2010 may have made the possibility of long duration Shuttles unlikely.]

10.5 NASA AND SPACE TOURISM

May 30, 2001 – To Mitch Daniels:

Space tourism clearly is not the most critical issue facing NASA in the short term, but at least temporarily it has caught the attention of the media. In future decades, it could become a central concern for NASA or a spinoff of NASA, just as air transport considerations dominate today's FAA. How broad this interest is within the electorate, outside of a small number of space activists, is not yet clear. At some point, however, the Administration may feel it needs to respond definitively to this issue. NASA, as you may have noted, has not covered itself in glory in its recent public statements.

Broadly speaking, two types of potential commercial activity in space can be defined. First, there are those activities that represent an expansion and improvement on services with broad, existing commercial foundations. Most obvious of these has been the explosion in satellite communications services since their introduction in the 1960s, building on an existing infrastructure of telecommunications upon which the country and the world already depended and on research and technology development related to launch vehicles and space communications hardware funded by the US Government. The use of satellites almost seamlessly added great new value to the existing infrastructure. The recent failure of Low Earth Orbit (LEO) satellite constellations to compete in the communications marketplace is the exception – at least so far – that proves the rule. Technical delays in the introduction of the Iridium, ICO, and Orbcomm LEO-based services failed to take advantage of their window of commercial opportunity which opened briefly in the mid-1990s, a window that was closed more rapidly than expected by the expansion of cellular phone coverage. Future LEO opportunities may slowly open, initially in areas such as long haul truck tracking, that will provide another commercial opportunity for these early LEO systems, particularly now that the initial investments have been written off [through bankruptcy filings] and the debt burden for the new owners of some of these systems is small. [In 2005, Iridium appears to be proving that this will happen.]

In this first category, there are examples of non-commercial space activities that have supported extensive commercial activities on Earth and include the use of satellites for weather observation, Earth observation and remote sensing, and navigation. These applications have been pioneered by means of government funding, but commercial ventures that use them are developing rapidly within existing infrastructures.

The second type of potential commercial activity in space is one that may offer a type of service with few if any existing commercial foundations. These might be collectively referred to as the "cure for cancer" opportunities. Although one should never underestimate the rate at which new arenas for research can pay off, it is likely that we will collectively need to be much more at home in the space environment than today, and understand that environment much more fully than we do now, before we can count on significant commercial returns on the ‘‘cure for cancer’’ opportunities. To the extent, however, that historical analogies provide any guidance with respect to future prospects, it is worth noting that the preponderance of human experience supports the belief that the greatest value to be obtained from a bold new enterprise will likely come from activities that are, initially, completely unforeseen. Our national history is replete with examples of this phenomenon. To offer only one example, Thomas Jefferson’s letter of instruction to Meriwether Lewis prior to the formation of the Lewis and Clark expedition of 1803–1806 reminds Lewis that a primary reason for the purchase of the Louisiana Territory, and of the expedition, was the hope and intention of finding a suitable water route between St Louis, Missouri, and the Pacific Ocean, thereby to effect appropriate transportation for the burgeoning *fur trade*. How many of us today believe this to have been the highest purpose to [arise] from the Lewis and Clark expedition? Yet, Jefferson was one of the most prescient men of his, or any, time. Similarly, it is more than likely that no one alive today can envision the advances in the human condition that will arise from the expansion of civilization into space. The possibility of energy resources coming from the Moon may be such an advance.

Earth remote sensing, mentioned briefly above, is the one area of potential space business which lies somewhere between the two major types of potential commercial activities discussed above, and on which several companies have bet significant investment on a commercial payoff. Ultimately I believe they are right [to make such investments], however, the existing infrastructure of the remote-sensing marketplace, although it exists for aircraft-based products, is not as large and as well integrated as that which existed in the 1960s for telecommunications. These initial entrants into the space remote-sensing market (Earthwatch, Orbimage, etc.) may have a close call, depending on the degree to which government becomes their anchor customer and on the success of their first spacecraft. At least there is no ‘‘cellular’’ system establishing a competitive new service.

Space tourism clearly belongs in the first category of potential commercial activity in space. Today, there exists a broadly based demand for tourist destinations and a large service industry that serves that demand, including transportation, accommodations, travel agencies, food service, etc. The primary questions facing such a potential space industry are ‘‘how to get started’’ and ‘‘how much of a role should taxpayer funds play in helping the industry to get started.’’ Let me suggest that there may be legitimate and relatively low cost roles for NASA in stimulating a permanent space tourism industry in ways comparable to its role in stimulating the space communications industry [in the 1950s and 1960s]. The following [list] summarizes each of the roles that might be considered for NASA. (With reference to my e-mail related to organizational structure in NASA [Section 10.4], this activity probably would be best coordinated out of the office of the Chief of External Relations.)

1. Re-activate the "Professional-in-Space" initiative of the early 1980s, inappropriately canceled after the *Challenger* accident in 1986. The new initiative could begin with the flight of Barbara Morgan, the late Teacher-in-Space Christa McAuliffe's backup, on the earliest feasible Space Shuttle mission. Ms Morgan actually is now part of the Astronaut Corps, having been selected in her own right. Thus, the initial step in the implementation of this action should be rather straightforward. In support of Astronaut Morgan's mission, NASA also should assist in the re-activation of the Teacher-in-Space network of classroom teachers that came into existence in response to Christa McAuliffe's selection as the first teacher to fly in space. If I remember correctly, this network of the over 100 state and territory finalists for the Teacher-in-Space selection had mobilized some 400 schools that were to interact with Christa during her flight.

   As a continuation of the Professional-in-Space initiative, NASA should establish relationships with a broad base of national professional societies and challenge those societies to help define the criteria for selection of candidates from their professions and the priorities for their flights to Earth orbit and/or extended stays at the International Space Station.

2. Undertake a research and technology development project within which interested and credible commercial entities would work with NASA to define the technical design and private financing options for a potential "Tourist Destination Module" for the Space Station. If, in the course of this initial design effort, it is clear that new technologies are required to make the Tourist Destination Module commercially viable then joint NASA/industry research and technology efforts could be initiated. Once technically and financially feasible approaches to these challenges have been identified, then the participating commercial entities could move the new technologies out from under the anti-trust umbrella of the NASA sponsored effort into the competitive market place. (This, of course, is the tried and true method of stimulating a new industry that NASA's predecessor, the National Advisory Committee on Aeronautics, used for half a century to advance the American aircraft industry.)

   In this context, NASA also should work with the Departments of Interior and Agriculture to examine the feasibility and necessary procedures for the potential operation of the Tourist Destination Module as a National Park, including the necessary qualifications of a resident 'ranger' to oversee the activities and instruction of visitors to the Module.

3. Undertake a research and technology development project under which interested and credible commercial entities would work with NASA to define the technical design and private financing options for a potential "Extra Passengers Module" for inclusion in the Space Shuttle payload bay. If, in the course of this initial design effort, it is clear that new technologies are required to make the Extra Passengers Module commercially viable then joint research and technology efforts could be initiated. Once

technically and financially feasible approaches to these challenges had been established, then the participating commercial entities again could take the new technologies out of the NASA sponsored effort into the competitive marketplace.

4. Undertake a research and technology development project under which interested and credible commercial entities would work with NASA, the Air Force, and existing launch vehicle suppliers to define the technical design and private financing options for a potential "Passenger-rated Expendable Launch Vehicle" derived from the nation's current and near-term inventory of such launch vehicles. If, in the course of this initial design effort, it is clear that new technologies, such as two-stage-to-orbit reusable vehicles, are required to make the Passenger-rated Expendable Launch Vehicle commercially viable then joint research and technology efforts could be initiated. Once technically and financially feasible approaches to these challenges had been established, then the participating commercial entities could move the new technologies out of the NASA sponsored effort into the competitive marketplace.

5. Conduct a series of workshops with interested non-governmental space interest organizations and appropriate entities of the National Institutes of Health to help develop the necessary criteria for qualifying candidate space tourists as being physically capable, safe and properly trained for space flight. These workshops also should examine and evaluate the feasibility of various methods for the initial selection of candidate tourists as well as the appropriate fees that should be charged for space excursions. (It has been proposed by some that the initial selection of tourists be conducted through a national lottery. It would seem that there would be many practical and legal difficulties in using such a process, however, the workshops should fully examine this option as well as others.)

   As baseline information for establishing fees, the cost (but not necessarily the price which might be set by auction or by subsidy) of a possible tourist flight should be fully and objectively delineated. If it is correct that the marginal (recurring) cost of each Space Shuttle flight is about $100 million and the effective Shuttle payload is about 50,000 pounds, then the [marginal] cost would be roughly $2000 per pound. (This is the usual airline method of pricing discounted seats for "tourists" given that the business traveler amortizes the fixed costs. Similarly, the government's primary purposes for flying the Space Shuttle would cover the sunk cost in infrastructure and normal operations.) Added to the marginal cost would be that of special equipment, training, in-flight support, etc. necessary to support a tourist flight. It may be interesting to note that the Russians reportedly charged [Dennis] Tito $20 million for his flight. If he and his equipment weighed about 200 pounds, this equates to about $10,000 per pound including the other cost items. The Russians, however, appear to be charging what the market will bear on a case-by-case basis.

Finally, NASA should also work with the Department of Justice and the Congress to evaluate legislative means of removing the threat of litigation that potentially would stifle the new space tourism industry and which would arise in the event of an accident involving a space tourist.

[In 2005, private sector entrepreneurs became increasingly active in trying to develop a space tourism business base for suborbital and Earth orbital flight. Further, the United States Congress passed and the President signed legislation that offers some liability protection for entrepreneurs involved in space tourism.]

10.6 AERONAUTICS

June 8, 2001 – To Mitch Daniels:

NASA and its predecessor, the National Advisory Committee on Aeronautics (NACA), have inherently contributed more to the nation's technological future than most expenditures of the taxpayers hard earned dollars. Indeed, they have opened doors of progress for the whole of humankind in many fields ranging from transportation to communications to healthcare to computers and beyond. They have honed the nation's technological edge in a vast number of fields and technologies that serve our economy, science, and national security. Since 1914, the NACA served to advance aeronautics primarily by providing an antitrust umbrella for industry to cooperatively participate in aeronautical research, test, development, and evaluation from which [American] industry proceeded to competitively dominate the field of aviation through the 1980s. Through the 1970s, NASA played a similar role in the far broader field of space-related technologies through its own development efforts in parallel with contracts to industry. In these efforts, however, NASA served largely as a contracting entity as well as research partner acting in parallel with contracted activities. These development contracts provided the hardware and software necessary for success in Project Apollo. A largely unanticipated benefit of the Apollo period was the temporary rejuvenation of the Nation's educational and research systems in science and mathematics.

Since Apollo, aeronautical research and technology development has remained a charge to NASA through the Space Act and a legislated responsibility by Congress. On the other hand, the decline in the competitiveness of the civil aviation industry in the US may well be a consequence of NASA's de-emphasis on cooperative aeronautical research since the 1970's and particularly since 1994.

Today, a review of this traditional approach may be appropriate in the context of the extreme consolidation of the domestic aircraft industry and rapidly increasing competition from foreign aircraft manufacturers. Rather than from another strong domestic company, intense competition now comes from Europe in large passenger aircraft and in military aircraft; from Europe, Japan and Brazil in small passenger aircraft and general aviation planes; and from Europe and Russia in rotorcraft. Europe's "A Vision for 2020" lays down a technological challenge in aeronautics that may need to be considered as a serious one.

It would appear that the concept of the government assisting in the pushing of the technological limits while industry applies advances to commercial endeavors is still valid. The government's clear interests in playing this role in aeronautics relates primarily to the role of aircraft required to advance our national security but also to the enhancement of exports and to strengthening our competitiveness in an important industrial sector. Aeronautical research and technology development, because of its extraordinary range of applications, feeds into many other engineering fields throughout the economy, including transportation in general, electronics, automobiles, energy production and conservation, electronics, etc. The question, of course, is to determine the "technological limits" for government to push without doing something that is more appropriate for the aircraft industry to do by itself with private capital.

Also, the need for new modes of "Intercity" mass ground transportation has gone unmet due largely to a perceived inability of such mass transport to compete in convenience with airlines and automobiles. NASA research and technology development that integrates magnetic levitation with aeronautical and information technologies may improve this competitive position dramatically by creating the economical means for very high-speed mass ground transportation. The primary rationale for embarking on this development path is the increasing congestion on many of our major interstates in highly populated regions. (Significant relief of congestion at many airports would be an added benefit but would be no substitute for more runways. We probably need both to meet demand projections.)

Recent private sector studies indicate that magnetically levitated, very-high speed ground transportation [passenger cars], with partial aerodynamic control and efficiencies, can get up to speed and stop in a mile or two of monorail track and can be built along the medians of existing Interstates [highways]. Scheduling of individual cars can be computer controlled so as to give demand regulated, non-stop service from many closely spaced commuter pick-ups to a primary destination and vice-versa. [This is] unlike trains in general and existing high-speed trains in Japan and Europe, [in particular]. These characteristics also alleviate the need to seek new right-of-ways, [avoiding] difficult environmental impact confrontations, along a currently congested Interstate either to expand the width of that Interstate or to construct a companion rail line. Florida's Interstate 4 between Tampa and Orlando is one example of the application of this concept that has been studied.[8] It would provide an expandable alternative to the current need to add eight more lanes to this [existing] eight-lane highway in order to handle the growth that has already occurred in this area.

(By the way, these types of maglev systems might be ideal ways of beginning the privatization of the Interstates, if you are so inclined. I see no reasonable way to meet the unfunded needs for repair and upgrade of the Interstate System unless logical, potentially profit-making sections are privatized and the users rather than taxpayers begin to bear the burden of new construction and maintenance. This is one of the few places where the French privatized system might be able to show us the way.)

The arenas, not including very high-speed ground transportation, in which a strong case can be made for expanded NASA activity in aeronautical research and technology development, in close cooperation with industry, appear to me to be as follows:

1. *Advances in technologies that could be applied to the current aircraft inventory and/or to the immediate next generation aircraft*, e.g., safety and error management systems and techniques, displays and data fusion systems, human factors investigations, simulation technology, active and passive composite materials, and increased strength and longevity and decreased weight of structural materials. Up on development of an aeronautical research and technology plan for the 21st century, [with] participation by relevant industry, the appropriate place for NASA sponsored research in each of these technology areas can be determined relative to that which could and should be finance by industry. One industry initiative that is on the cusp of whether NASA should be involved or not is the Boeing proposal for a Mach 0.95 "sonic cruiser." It would appear that it is important for this initiative to be successful and if it is, there may be significant defense applications. Boeing will need major advances in airframe design and testing, materials, and engine design to be successful. To my knowledge, Boeing has not asked NASA to be involved, but it is a possibility worth some private discussions.

2. *Advances in environmental protection with respect to noise and pollution.* This is a currently very contentious area, particularly in the case of aircraft noise. In spite of the fact that US aircraft companies have made more progress than anyone else, Europe, as you may be aware, is using the so-called "Chapter 4 noise negotiations" to try to restrict the use of older US built aircraft, worldwide. On the pollution side, jet engine technology has been advancing rapidly, but someone will always complain.

   For short and medium haul routes, there may be a potential for a fusion powered propeller driven aircraft if a particular technology called Inertial Electrostatic Confinement (IEC) fusion [helium-3] matures as forecast. As this area of non-radioactive nuclear energy development has been of no interest to DOE, it might be something for NASA to look at in the aeronautical context until it is clear what the potential may be. NASA and DOE are both pursuing other IEC applications for space propulsion and terrorist weapon evaluation, respectively, however, budgets for this work are very limited at the present time. The Japanese have an aggressive IEC research program, but it is not clear yet what their aims might be. [In 2004, it has become clear that Japan is concentrating on landmine detection, using IEC devices to generate neutrons from deuterium–deuterium fusion.]

3. *Hypersonic technology research* in cooperation with the Air Force may lead to advanced generations of commercial and military aircraft in the early part of this century. It is an attempt to blend both aeronautical and space technology with the potential for future, partially ballistic commercial and military flights that go from point to point globally in tens of minutes to less than two hours. [In 2004, NASA withdrew from a continuation of this research after a successful demonstration of flight of the X-43 at Mach 10.]
4. *Advances in rotorcraft* (helicopters, etc.) technology that would concentrate on increasing the US share of the current $5.5 billion world market with future generation helicopters. I am told that we currently have about a $65 million favorable balance of trade in this area. NASA's recent announcement that it is stopping rotorcraft research, including backing out of a 36-year cooperative research program with the US Army, and rapidly increasing competition from around the world, seriously threaten this industry.
5. *Very high-speed mass ground transportation* (see preceding discussion).

Under the previous Administration, NASA's budget for Aeronautics went from about $1 billion in 1994 to $380 million this year. Although I am sure that some tightening up was warranted, my personnel experience with managing people in this field as part of NASA's energy efforts in the mid-1970s was that it is a far more efficient arm of the Agency that most others. NASA's statements that it is focusing on large, aerospace craft that change configurations like a bird and have engines that change type as new flight environments are reached sounds good but has been met with derision by many in the field in view of what are felt to be more urgent needs for the future of the US industry and military.

10.7 SPACE BIOMEDICINE

June 21, 2001 – To Mitch Daniels:

Assuming that humans will be active in the space environment for the foreseeable future, then the practice of medicine in space will be an essential part of such activity. Various forms of medical treatment from time to time will be required for long duration occupation and research on the International

Space Station, long duration flights to Mars, long duration human bases or resource extraction settlements on the Moon, and even extensive space "tourist" activity. Ultimately, medical treatment will become the responsibility of the sponsoring commercial or governmental entity. Meanwhile, NASA currently retains the responsibility for assuring that quality and ethical scientific research is conducted relative to (1) the physiological basis for preventive medicine and medical treatment in space, (2) countermeasures necessary to avoid adverse consequences of exposure to the space environment, and (3) terrestrial applications of knowledge gained from such research.

On Earth, preventive medicine and medical treatment are based on an accumulated and ever expanding understanding of human physiology in a variety of terrestrial environments, all of which have [four standard] things in common that are absent from space environments currently accessible to humans.

1. *The acceleration due to Earth's gravity, i.e., "one gravity."* In orbital space, this acceleration is effectively zero. (The very small effects of spacecraft mass create what is called a "micro-gravity" environment.) The Moon has one-sixth and Mars has three-eighths of Earth's gravity, respectively.

2. *The standard mix of gases in the Earth's atmosphere.* For various reasons, spacecraft and space habitats have used low-pressure oxygen or, more commonly now, various mixtures of oxygen and nitrogen, maintained close to the Earth's sea level atmospheric pressure. Both such atmospheres have variable amounts of transient carbon dioxide that has not yet been removed by scrubbers of various kinds. Other gases, more properly called pollutants, are present, particularly in Russian-built modules. There are cogent arguments why future spacecraft should return to the Apollo-era low-pressure oxygen atmosphere, however, that is an issue for future discussion as two gas atmospheres are now the norm.

3. *The protection from solar particle radiation and galactic radiation provided by the Earth's atmosphere.* There is some protection from solar charged particle radiation in low Earth orbit due to particle interaction with the Earth's magnetic field. Once outside the influence of that field, however, protection from all forms of space radiation largely will come from the nature and mass of materials making up the spacecraft or covering lunar and Martian living quarters. The very limited Martian atmosphere will provide some but not complete protection.

4. *The broad spectrum, dominantly about 7.8 Hertz, electromagnetic field that exists between the Earth's surface and the ionosphere* due to the integrated effect of global lightening discharges (Schumann Resonance).[9] No research to date has explored the possible effects of the absence of this field in space, however, related research on Earth has suggested that human physiological processes may have evolved to use this field. It may not be coincidence, for example, that human brain wave frequencies cluster around 8 Hertz and

> that exposure [to] a similar frequency of pulsed electromagnetic fields affects human mental performance.

The absence of one or more of the above terrestrial environmental "standards" is clearly the cause of what is properly called the "space adaptation syndrome" but is more commonly and incorrectly referred to by NASA as "space motion sickness." The variety of symptoms related to this space adaptation syndrome, including generally short term symptoms of motion sickness, have been experienced to varying degrees by all astronauts and cosmonauts who have been in space. In addition to the nausea and headaches commonly associated with motion sickness in a one gravity field, syndrome symptoms include fluid shift to the upper body, loss of appetite, changes in red cell mass and blood chemistry, decrease in bone density, loss of muscle mass (including heart mass), spinal lengthening, and minor hallucinogenic phenomena.

The short-term effects of motion sickness appear to be significant in about 40% of those exposed to space, but largely disappear in 3–4 days except in about 2% of the cases. Long-term adaptation apparently affects all astronauts and cosmonauts, but to different degrees on an individual basis. Terrestrial re-adaptation relative to each of the space adaptation symptoms occurs over times roughly proportional to the length of time spent in space. The closest terrestrial analogy to most of the long-term adaptation symptoms and the re-adaptation process is prolonged and absolute bed rest by healthy individuals.

In space, medical treatment of ordinary human disease and injury has no base of comprehensive understanding of human physiology comparable to that available in the terrestrial environment. 35 years of study by NASA and the Soviet/Russian programs have not provided a credible scientific understanding of (1) the physiological foundations of space adaptation syndrome, (2) the interactive effects of weightlessness, radiation exposure, pollutants, [and] atmospheric gas mix, and (3) other known and unknown factors. Nor is there understanding of what may constitute the best mix of countermeasures against the adverse aspects of the syndrome. Thus, to put it another way, no [scientific] basis for the practice of space occupational medicine exists. Consequently, the benefits to our aging population of understanding space adaptation syndrome also have not been realized.

These failures are the result of several historical factors inherent in NASA's approach to using the hundreds of millions of dollars directly or indirectly budgeted to space biomedicine, as summarized below:

1. There was a sharp contrast between the lack of obvious adaptation symptoms during the Mercury and Gemini flight programs and the motion sickness-like reactions of many astronauts during early Apollo flights [during which crewmen could move around vigorously]. This anomaly led NASA's fledgling space biomedicine community to prematurely conclude that the syndrome was merely another form of terrestrial motion sickness induced by multi-sensory conflicts in the brain's fusion of information from various sensors humans use for balance – the inner ear (vestibular), vision (ocular),

and muscular (proprioceptive) systems. The initial exposure to a weightless environment negates the value of the gravity-sensing portion of the vestibular system, i.e., the otolith. When a weightless person moves, a variety of multi-sensory conflicts occur and produce symptoms of motion sickness. As a consequence, the vestibular system became the nearly exclusive focus of early NASA space biomedical research. The vestibular research community became entrenched and other lines of investigation were largely blocked until well into the era of the Space Shuttle. Only in recent years have investigations of other affected body systems – cardiovascular, musculoskeletal, biochemical, neurological, immunological, etc. – received limited consideration. Even now a full recognition of the broad systemic nature of space adaptation syndrome appears absent from NASA's space biomedical research efforts. For example, a search of the web pages for NASA's Office of Biological and Physical Research does not disclose an obvious, scientifically credible, long-range coordinated plan to take full advantage of the opportunities presented by the Space Shuttle and the International Space Station as related to comprehensive preventive medicine and medical treatment in space.

2. NASA has consistently refused to avail itself of the opportunities and credibility that would come from a full research alliance with the National Institutes of Health. This refusal appears to be entirely of a bureaucratic nature – "I don't want those people in my knickers," to quote a former Administrator when presented [by me] some years ago with a plan for a NIH–NASA cooperative research program pre-approved by the NIH. There also is an element of fear, I suspect, that the NASA sponsored researchers and research could not measure up to NIH standards, a fear that would be well founded in many instances. Unless drastically upgraded, many NASA sponsored research projects probably would not pass NIH peer review, a necessary part of any world-class biomedical research program. The bottom line, however, is that NIH has a world-class system of selecting and managing biomedical research projects and NASA has a world-class, indeed unique, facility in space for undertaking such projects. It would seem to be a marriage worth pursuing.

3. Most of NASA's investigations of the space adaptation syndrome are tainted by conflicts of interest inherent in the use of its own astronauts as test subjects. Most astronauts understandably are reluctant to speak candidly of their highly individual adaptation symptoms in fear of being taken off flight status. This concern has its origins in the military flight culture in which flight surgeons can ground a pilot with the stroke of a pen – "Don't tell a flight surgeon anything," is the first advice a student [military] pilot receives from his or her senior peers. There are enough real examples of what appears to be arbitrary groundings, including some astronauts, to continuously reinforce this perception.

4. Invocation of a privacy restriction on all biomedical data collected on individual astronauts (including John Glenn's recent flight, by the way) prevents fully informed outside independent analysis of human response to space flight. This privacy restriction is totally counter to accepted scientific practice in which independent replication of research results is a fundamental criterion of good science. Space adaptation syndrome is so individually variable that independent analyses of collected data must be tied to individual medical histories and changing responses from flight to flight. It is not clear that privacy regulations really should be applied to taxpayer paid volunteers such as the astronauts, however, their invocation has seriously compromised the scientific credibility and value of NASA's human biomedical research to date.

Suffice it to say that the Soviet/Russian efforts in this field have even more problems and biases with respect to scientific credibility than do NASA's. The greatest value of their work, and it is considerable, is the empirical evidence that, in spite of the adverse effects of space adaptation, humans can tolerate exposures to the space environment for periods in excess of one year.

In order to significantly improve NASA's approach to space biomedical research from this point forward, the following should be considered:

1. Create a partnership with the National Institutes of Health, the Food and Drug Administration, and the private sector to develop a scientifically credible understanding of human physiology in space and the countermeasures necessary to mitigate the adverse effects of human adaptation to the space environment, including micro- and fractional gravity environments and space radiation effects. The National Space Biomedical Institute in Houston should be jointly funded and managed within this partnership rather than having its funding controlled by the Johnson Space Center.

2. A cadre of physician astronauts (minimum of 12 or possibly 24) should be recruited as both investigators and test subjects and should conduct a broad protocol of investigations on the ISS. This protocol should be overseen and peer-reviewed by the NIH. The physician astronauts should return to the ISS repeatedly (another argument for a long duration shuttle capability) until space adaptation and its countermeasures are sufficiently understood to support missions to Mars and settlement on the Moon. Barring any life-threatening situations, the career success of the physician astronauts would depend on the quality of their research rather than what was found out about them individually.

3. The primary research objective for NASA's use of the ISS should be space biomedicine, including (a) the understanding of space adaptation to micro- and fractional gravity environments and potential countermeasures to such adaptation and (b) studies related to aging. In this context, the Skylab astronauts of the 1970s should be recruited for an ISS reflight of the biomedical protocols in which they participated.[10] Further reflights of

this special cadre should be made on about 10-year intervals as long as feasible.

4. Test subject participants in space biomedical research should be required to waive any and all medical privacy demands so that the entire biomedical community can participate in the analysis and interpretation of research information. An analysis of federal privacy regulations should be conducted to determine if existing medical records of the astronauts as they relate to previous and future space flight are covered, in fact, by such regulations. If astronaut records are so covered, it should be determined what changes are appropriate and feasible in order for qualified outside researchers to have access to such records and to publish the results of their studies.

[In 2004, future research in space biomedicine has become focused on work using the International Space Station, in response to the President's Exploration Initiative and the envisioned retirement of the Space Shuttle around 2010.]

10.8 SPACE LAUNCH INITIATIVE

July 7, 2001 – To Mitch Daniels:

[The Space Launch Initiative,[11] briefly part of the history of NASA's efforts to move beyond the Space Shuttle, is left as part of this e-mail exchange with the OMB because its implementation was symptomatic of the disarray in NASA's management systems just prior to President Bush's announcement of his Moon–Mars Exploration Initiative. In the years since, it is not yet apparent, but is to be hoped that NASA has eliminated these deficiencies. The rushed, incoherent, and often unexplainable activities related to NASA's attempts to solicit proposals in response to its various Broad Agency Announcements (BAA), and to organize its "strategic roadmap" and "capabilities roadmap" development for the Exploration Initiative,[12] suggest continued absence of adult supervision unlike that which was present during a similar period in the early days of Apollo. On the positive side, the levels of response to the BAAs and of interest in participating in the "roadmapping" teams have been extraordinary, indicating a pent up desire in and out of the broad space community to help NASA succeed.]

NASA's Space Launch Initiative (SLI) [now canceled and replaced by the Crew Exploration Vehicle (CEV) project as part of the Exploration Initiative] conceptually represents exactly the type of new activity that the Agency should be undertaking. The future in space, whether in Earth orbit or beyond, will be determined by the cost and reliability of launch services whether provided by commercial interests or the government. The "grapevine" suggests that

OMB's fingerprints are all over the stimulus of this concept and, if true, your Office is to be commended. Properly planned and managed, SLI has the potential to catalyze the development of a viable industrial and service base in space transportation, to support national security requirements, and to lay the foundation for potential Presidential initiatives in deep space.

Relative to the question of why NASA and not industry should develop the next generation of space transportation capabilities, it has been convincingly shown that industry cannot yet do the job alone consistent with customary amortization schedules and expected returns on investment (ROI). The market is not yet there, nor forecast to exist in the near future, which could support the number of flights required for the private sector to compete in the financial markets for use of capital. Thus, at least through the next generation of reusable launch vehicles, the government must carry the fiscal obligation for this development as it has for the creation of major national infrastructure in the past. Air transportation, the Interstate Highway System, Air Traffic Control System, and locks and dams on major rivers are four examples of infrastructure that have been or could be privatized and commercialized after the initial federal expenditures.

The obvious question, however, in view of the management related failures of the X-33 and X-34 reusable launch vehicle (RLV) efforts and of two recent Mars Probes, is NASA prepared to go forward successfully with SLI?[13] As the first round of $790 million in awards to industry and academia has occurred, answers to this and related questions are more urgent than ever. To the first order, we have no choice but to be successful with SLI if we intend to operate the International Space Station (ISS) indefinitely. Even if everything goes right, the Space Shuttle will be required for ISS operations for at least 10 more years so its safety and avionics upgrades must go forward largely independent of SLI. The potential of adding a long duration (up to 90 days) orbital capability to the Shuttle fleet also may be of interest as discussed in a previous NASA Situation e-mail [Section 10.4]. Because the option exists to extend the life of the Shuttle fleet another 20 years or more through refurbishment and upgrades, additional options exist for modifying the objectives of SLI in consideration of possible future Presidential initiatives. [President Bush's Exploration Initiative envisions retirement of the Space Shuttle in about 2010. The long delay in the Shuttle's return to flight after the *Columbia* was lost, as well as probable delays in the implementation of the Initiative, probably will delay this retirement for several years.]

At the outset, the question also exists as to whether NASA's interpretation of the aim of SLI is correct, i.e., that SLI is primarily a launch related "technology" development program rather than a "capability" development program. As will be discussed further below, the program might meet its initial objectives more quickly and with less risk if it was revised into a near-term "capability" development program and a long-term "technology" program. The near-term program to demonstrate low cost reusable launch capabilities could, of course, feed off the long-term program if and when bottlenecks appeared in the use of the existing technology base. The key here, of course is "reusability." It is mathematically demonstrable that "expendable launch vehicles" (ELV) cannot meet the commercialization objectives of SLI. It has yet to be demonstrated, of course, that the theory that reusable launch vehicles can be commercial is correct. In this context, engineering theory related to the useful payload fractions possible with near-term technologies, as well as lessons from the X-33 experience, indicate strongly that SLI initially should emphasize two-stage-to-orbit (TSTO) reusable concepts over single-stage-to-orbit (SSTO) [concepts].

As a means to examine the current status of SLI and NASA's management of it, it may be useful to examine the most recent Congressional testimony on these subjects. The major specific points raised by June 20, 2001, testimony before the House Subcommittee on Space and Aeronautics are summarized below (underlined) with some added comments based on my recent look at related information and discussions with knowledgeable engineers outside of NASA. Some suggestions on what to do with all of this follow this summary.

Allen Li (General Accounting Office)

1. *NASA apparently did not develop detailed "cost estimates, acquisition plans, and risk mitigation" plans prior to the first SLI contract awards.* The lack of such early estimates and plans, and the lack of regular updates to them during the contract periods, appears to be a major contributor to the failure of the X-33 project and the X-34 engine [development] project managed out of Marshall. (The primary problem with the X-34 program was the failure of the Marshall-led engine development, not the vehicle itself.) NASA worked these two programs with conflicting financial assumptions that (1) its [NASA's] costs could be fixed, (2) contractor costs could be variable, and, (3) in the case of Marshall's X-34 engine development, development costs and delay costs could be open-ended for contractor and NASA alike. With these conflicting assumptions and without a rigorous analysis of financial risks and commensurate risk management plans, very lax financial control of both projects resulted.

2. *It is not clear that NASA has faced up to the "coordination and communication" required to oversee the work of 22 different SLI contractors, including the development of competing space architectures.* Coordination and communication problems also contributed to the demise of the X-33 and X-34 projects as well as the loss of at least one of the Mars probes. This appears to have been particularly an issue in the design of the X-33's failed composite fuel tank.

3. *NASA apparently has not prepared "rigorous program management plans or program commitment agreements" for SLI as a whole or for the individual contractors.* Absent from the X-33 and X-34 projects, these plans and agreements are the essential foundation for good program management. The management plans lay out the program's resources, data management, risk management,

test and verification, and review schedule. Commitment agreements define the technical, schedule and cost commitments as well as the overall acquisition strategy relative to NASA and each contractor as well as any required interactions between contractors.

4. *''Configuration control plans and performance measures,'' or metrics, apparently have not been established by which the progress of both NASA and its SLI contractors can be evaluated.* Although specific configuration control of hardware and software deliverables cannot normally be established until after the first formal design review, the detailed planning for such control should be part of program management plans. Performance metrics, of course, can and should be established for each phase of a development project, including the first phase. Clearly, the lack of early configuration control and of performance metrics for the NASA managers as well as the contractors, and their periodic revalidation, were major problems with the X-33 and X-34 efforts and probably also has been the major contributor to the surprise overruns in the International Space Station program.

Steven Hoeser (former DC-X Project Team Member)

1. *NASA should consider changing its primary objective for SLI from primarily technology development to primarily ''capability development.''* Capability development would set certain performance, cost and reliability targets that depend on the integration of available technology to attain a particular capability whereas technology development sets targets based on a desired capability that is beyond current technology. Both have their place and, clearly, if available technology cannot provide a desired capability, the two approaches will merge and focus on a specific requirement. Technology development, of course, tends to be [the] more research oriented and open-ended of the two approaches and has traditionally characterized the aeronautical research and technology development side of NASA's house.
2. *If SLI became a capability development program, this would probably lead to an exclusive near-term focus on two reusable stages to get to orbit.* The X-33 experience as well as earlier independent analyses indicate that engine and materials technologies are not yet available that would make possible a single stage to orbit which could deliver a useful payload mass. One or more target designs of a single stage to orbit, reusable launch vehicle could be developed to guide the long-term technology development, however, in order to stimulate a commercial reusable launch service industry, near-term resources would be focused more productively on two stage to orbit capability development.

T.F. Rogers (Space Transportation Association)

1. *NASA needs to find a means to introduce into its normal engineering based planning and management of SLI a full understanding of how the non-aerospace private sector*

conducts its business and financing. If the ultimate existence of a competitive, financially stable, commercial space transportation and services industry is a primary goal of SLI, then the fundamentals of what that means must be part of the program and its performance metrics from inception.

2. *A portion of the SLI program should be set aside for work in recognition that, if SLI's primary goal of a competitive, financially stable, commercial space transportation and services industry is realized, and if the Space Shuttle and International Space Station operations are ultimately privatized, NASA will need a variety of new space launch and propulsion capabilities to move national space activities back to the Moon and beyond.* Although it would be premature to suggest a Presidential initiative along such lines today, the only way to be ready to implement such an initiative is to begin to build and rebuild the necessary technical and managerial foundations within NASA and to stimulate the private sector industrial base and entrepreneurial partnerships necessary to minimize the expenditure of tax dollars on this effort. Almost all professional observers would agree that the lack of affordable, reliable, predictably available space transportation still represents the single largest impediment to a space defense force, to the expanded use of near-Earth and cislunar space, and to the human settlement of the solar system, if, indeed, that becomes an objective of this nation or the human species. Many have pointed out that after over 40 years of space flight, we still lack the space equivalent of aviation's DC-3 which appeared only about 30 years after the Wright Brothers first aircraft flight – with government's assistance, by the way.

Sam Venneri (NASA Associate Administrator for Aerospace Technology)

1. *The SLI goals are to reduce reusable launch vehicle payload launch costs from the Space Shuttle's $10,000 per pound to $1000 per pound, to have a reliability (risk of crew loss) of 1 in 10,000, and to have a "commercially competitive vehicle operational" by 2010.* Although internal documentation may exist, these goals do not appear to be based on any fundamental analysis of what may be feasible. The goals, in fact, may be incompatible.

Dennis Smith (Space Launch Initiative Program Manager at Marshall Space Flight Center)

1. *"The SLI employs a bottoms-up, rigorous systems engineering approach to define multiple competing architectures and links all technology investments to those systems."* This statement appears to be contradicted by GAO's analysis (Allen Li, above). [Note: NASA probably should avoid its repeated use of the terms "investment" or "to invest" when referring to expenditures of taxpayer dollars for generally intangible returns, however important they may be. I understand the public relations reasons that it does this, but these are terms that probably should be reserved to business and financial related

issues where a true financial return on investment is anticipated. Their use otherwise turns off professionals and will become confusing when truly commercial endeavors are integrated into NASA's development and operational activities. NASA's "expenditures" are made to further national objectives in space and aviation. They may engender true returns on investment in the private sector, but that is an indirect effect however important it may ultimately turn out to be. The government's indirect financial returns are through the tax code, through lower cost services provided by the private sector, or through new technologies that provide a new capability at lower cost.]

2. *The phrase "rigorous systems engineering approach" is used repeatedly with reference to SLI program management.* In light of the X-33 and X-34 experiences and the GAO's observations given above, it is not clear that NASA any longer understands what this phase means and, in fact, should not be used as a synonym for "rigorous program management." In fact, this testimony appears to incorporate "buzz" words and phrases related to program management and commercialization constraints without providing the detail necessary to build confidence that "rigorous" program management is in place for SLI along with a full understanding of what is necessary for an "architecture" to be commercial. Actually, the fundamental components of successful program management (program management plans, program commitment agreements, cost estimates, acquisition plans, risk management plans, configuration control plans, and performance metrics) are not mentioned or emphasized.

   Further, there appears to be two systems of external review, the External Requirements Assessment Team (ERAT) for validating the "rigorous systems engineering approach" and the Non-Advocate Review (NAR) for assuring "continued integration of the overall effort." I believe in external review and oversight of programs as complex as SLI, however, a properly structured management system should provide internal "validation of requirements" and "assurance of integration." External review should be at a level that will identify major holes in the program or its management or new technical directions that should be explored. If NASA can't handle the routine management functions, it should not be doing the program.

3. *"Many of NASA's unique mission requirements cannot be served by commercial vehicles alone, since they often require human presence in space."* This statement shows that the management leadership of SLI does not understand that other humans besides astronauts going into space will be part of what makes a commercial reusable launch vehicle "commercial." NASA's "unique mission requirements" thus become less unique in the commercial world.

4. "*Data rights, as specified under [SLI's NASA Research Announcement] NRA8–30, are retained by the government."* Why? If a primary purpose of SLI is to

commercialize launch services, why would NASA want to hold the data rights? This is important to future investors and, unless something has changed, this is contrary to NASA's past policy relative to intellectual property derived from its programs.

5. "*The Space Shuttle will be utilized as a 'lessons learned' reference point.*" Clearly, this is appropriate, however, no mention is made of using the X-33 and X-34 and International Space Station as "lessons learned" reference points. Hopefully, they will be so used and Marshall just doesn't like to talk to Congress about sordid past history.
6. "*Private industry will not and cannot make adequate investments in space transportation risk reduction and technologies. The aerospace industry is dependent on NASA pursuing technological advancements to maintain or improve US competitive capability in the international launch market.*" This is self-serving malarkey. Private aerospace industry and other financial entities make investments independent of NASA depending on their estimated return relative to the apparent risk. This has been done for many space systems (communications satellites, remote-sensing satellites, and small launch vehicles, in particular). Risk reduction is always on the minds of industry and its investors. This is another indication that NASA is ill-prepared at this moment to integrate commercial fundamentals into SLI.

House staff brief to Members for the hearing

1. *There appears to be a conflict between NASA's desire to use SLI to stimulate the creation of a low-cost, private sector RLV to meet its near-Earth human space flight needs and its desire for a Space Shuttle replacement.*
2. *A conflict in SLI also appears to exist between NASA's tendency to design for maximum vehicle performance with less consideration for potentially more important commercial cost factors like reliability and operability.*
3. *NASA's unique human space flight needs may conflict with commercial realities for a reusable vehicle unless confronted fully in the initial SLI program definition phases.* If NASA is the only customer, a commercial launch capability for human space flight is a non-starter.
4. *NASA must resist the temptation to avoid "building tested, demonstrated, and validated hardware" in the early, study phases of SLI.*

[Suggestions]

Stepping back from what appear to be legitimate concerns from several sources about the SLI as presently conceived and implemented by NASA, several actions might be considered.

First, reconstitute SLI into a capability driven effort, focusing on more near-term, fully commercial two-stage-to-orbit vehicles, both reusable, using the existing and near-term technology base as a first choice unless new technology is clearly needed and warranted either from a requirements or a cost perspective. The aim would be to fly two or more prototype designs within a reasonable time frame, possibly by 2005. [This happened in 2004 with respect to suborbital flight in the X-Prize competition, but was entirely funded by private entrepreneurs.] NASA's role should be to encourage and assist in design and technology as many commercial entities as possible that meet pre-established criteria for potential technical and financial viability. Based on history, it appears that the first flight article of a man-rated, Space Shuttle-class, two-stage-to-orbit reusable vehicle with a dry weight of ~200,000 pounds (~90 tonnes) would cost ~$100,000 per pound to develop, or ~$20 billion over about 7 years. With much better management within NASA than we have seen in the past few decades, we can hope that this total cost would be somewhat less. For example, lessons learned from the Shuttle and X-33 experiences and new financial controls should lead to lower cost designs. Further, if the development milestones related to future commercialization are met, one could expect to see the financial markets begin to take an increasing interest.

Second, undertake true research and technology development efforts by NASA/Industry teams (1) as technical constraints on near-term commercial, two-stage-to-orbit RLVs are identified, and (2) as the needs of next generation commercial RLVs are delineated by the near-term program and by space architecture studies conducted in partnership with the private sector. In the second case, NASA's role is very much like its traditional role in aeronautical research and technology development, supporting the industry as a whole.

Third, clean up, modernize, and streamline NASA's and Marshall's management of SLI in accordance with successful management practice for technically complex projects and the lessons learned from past successful and unsuccessful endeavors, particularly Apollo, X-33, X-34, and ISS. As part of this process, examine the feasibility of going back to the Apollo era technique of having teams of NASA engineers working on the design, [production and test] phases of specific projects in parallel with contractors for those projects. This system of parallel teams not only creates a beneficial tension between the teams, but provides two informed points of view to senior managers when problems develop or changes are proposed. Also, with the experience of several decades and several major programs behind us, I would suggest that "program management" authority always remain at NASA Headquarters with "project management" parceled out to appropriate Centers based on their history and current capability base. Having program management assigned to one Center to which other Centers report just doesn't fit with the practical reality of inevitable technical and political competition between Centers.

Fourth, reorient portions of the SLI funding stream to support a potential Presidential Initiative related to deep space. Some mainline SLI efforts also can be coordinated with the aims of such an initiative in order to meet a range of needs. For example, the first stage of a Shuttle class (<20 tonnes to orbit) two-stage-to-orbit vehicle also probably could be the first stage of a heavy lift (>100 tonnes to orbit) reusable vehicle for deep space applications. Also, this first stage might become the basis for a suborbital terrestrial transport with both commercial and national defense applications.

Fifth, utilize a portion of the SLI funding stream to develop a long duration capability for the Space Shuttle [see Section 10.4] and to refurbish, upgrade, and enhance the safety and reliability of the Shuttle fleet. This fleet will probably be needed for Space Station and satellite servicing and repair until near 2020 depending on progress in SLI.

[In 2004, the SLI program disappeared, in part, in response to the President's Moon-Mars Exploration Initiative. Its lessons, however, will be no less valid in the implementation of that initiative.]

10.9 SPACE SCIENCE

July 2, 2001 – To Mitch Daniels:

The role of scientific research funded by NASA has, of course, been related to pure science (such as astronomy) and applied science (such as much of early lunar research). Pure science, of course, is undertaken for knowledge's sake alone on faith that some of that knowledge [will] improve the human condition or the human spirit. Applied science, on the other hand, has a specific need in mind however basic the research may be and, in the case of space, has been largely in support of human [or robotic] space flight. Clearly, some pure science may eventually have a direct application to later human space flight, [and] studies of space radiation and the Martian surface come immediately to mind. Similarly, some applied science provides significant scientific insights related to the Earth, planetary, biomedical, solar and other "hard" sciences. The distinction, however, between pure and applied remains a useful means of highlighting organizational differences [in NASA].

In the pure science arena, NASA's activities related to the space environment primarily overlap those of the National Science Foundation (NSF) and the National Institutes of Health (NIH). In applied space science, overlap with the responsibilities of other agencies is usually minimal and supportive and usually involves some of the activities of the National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DOD), the Department of Interior (DOI), and the Environmental Protection Agency (EPA).

[Pure Science]

With respect to the conduct of pure science activities of NASA, one has to say that those programs are in much better shape based on performance than the human space flight side of the house. This is true even taking into account major cost estimation and [financial] control problems and the two recent Mars mission failures. Both the failed Mars probes were under the management of the Jet Propulsion Laboratory (JPL) and clearly suffered from lapses in good management practice both there and at Headquarters. [In 2005, JPL's performance has improved markedly, particularly with the success of the [both the] Mars Exploration Rovers.]

We can hope that the recent changes in JPL senior management and NASA's decision to provide increased competition for management assignments from the Applied Physics Laboratory and elsewhere will improve JPL's performance on future mission assignments. A closer look by a new NASA Administrator may disclose significant problems with program and financial management, however, from a distance, things could be a lot worse given the horrendous problems elsewhere in NASA.

Although I am sure that their particular advocates would say that too little money is spent on each of them, the astronomy, space and solar physics, and outer planets flight programs have had a long string of successes and have advanced human knowledge by immeasurable degrees. Recent robotic investigations of the Moon from orbit and of Mars from orbit and on the surface similarly have been and continue to be remarkably successful once in operation. The huge and growing attendance at various lunar and planetary conferences (reporting research financed mostly by funds bootlegged from other sources, I suspect) attest both to this success and the continuing enthusiastic scientific interest in solar system science and exploration. Unfortunately, there are signs that the cost estimation and control problems of other programs are showing up in the pure science projects as well. The Next Generation Space Telescope and the Mars program costs growth beyond their current caps are cases in point. These financial "mishaps" make it nearly impossible to maintain a consistent flow of quality future missions in the space science pipeline. Here as well as everywhere else in NASA a rejuvenation of project and financial management is the first step before much new work can be undertaken. The "faster, cheaper, better" credo of the 1990s demanded far "better" management attention than it received if it was to have any hope of succeeding.

The most significant technical issue for the exploration of the outer planets, such as the current interest in Pluto and Europa, and long surface stays by robotic craft on the Moon and Mars is long-duration power, both for space propulsion and for electricity and heat. Instead of concentrating on solar power systems that get exponentially less useful the farther one goes from the sun and can't be used in the dark on the Moon and Mars, NASA must once again become the champion for nuclear systems for propulsion, power, and heat if this exploration is to continue beyond those spacecraft currently active. This battle was won several times before but NASA has since abandoned the field to the anti-nuclear political extremists. The Department of Energy's recent decision to resume production of Plutonium-238 (now imported from

Russia) needed for deep space radio-isotope thermoelectric generators (RTG) is a necessary step in the right direction along one of several important space power paths. This action is an encouraging sign, along with the NASA/DOE plan to contract for the design of a new generation of RTGs and NASA's work on fission (in cooperation with the DOE laboratory at Los Alamos) and fusion propulsion systems at Marshall Space Flight Center.

In terms of science priorities, the astronomy community has led the way in unifying behind a set of flight program objectives and sticking to them in its long-term advice to NASA. Other discipline communities finally appear to be learning by astronomy's example. [This] should eventually help the OMB and NASA (and Congress, of course) focus on what appears to be important based on what is known. These communities and NASA, however, must always retain enough flexibility to adjust priorities based on new findings.

[Applied Science]

For better or worse, NASA-developed space technology has formed the foundation of much of worldwide satellite communications, weather and climate forecasting, environmental monitoring and regulation, public land management, energy and mineral exploration, fisheries management, and land use monitoring. This previous dependence on US-developed technology is changing rapidly with specific long-term initiatives on the part of Europe and Japan [and China and India] now in place. The US satellite technology is becoming less and less the standard in the world. We should examine seriously the re-invigoration of research and technology development in cooperation with industry in this arena with a full understanding of the consequences of not so doing.

Applied earth and engineering sciences have changed our ways of doing the Earth's business, providing services, and regulating human activity in modern times. As a consequence, NASA should begin bending over backwards to ensure that data collected from its space systems is presented to the public in as objective a way as possible. This has not always been the case with the leading example being data related to climate change. As a case in point, the observed climate warming over the last century is confined to the near Earth surface portion of the atmosphere and is not seen higher in the atmosphere (the troposphere) after nearly two decades of satellite data collection and a longer period of balloon data. This is contrary to predictions from current models of atmospheric circulation and has been largely ignored or dismissed out of hand by the political advocates of global warming many of whom are scientists who should be more objective. Further, many past measurements of ocean surface temperatures using sensors in ship cooling system intakes which are included in these warming trends have recently become highly suspect. As the Administration obviously is aware, these are just two of many reasons that we must be cautious in our reaction to predictions of global warming, but that we must always be prepared to adapt technologically to climate change. Geological history tells us that some climate change, particularly rapid cooling, may occur unexpectedly over a decade of time following a period of warming. This now appears to be the sequence that led to the Northern Hemisphere's Little Ice Age of the 1400–1800s and which we still [may] be coming out of at present. This illustrates how NASA, as well as other Agencies, could profit by searching for more and better historical and prehistorical surrogates for modern climate data and trends.

Over the last decade, NASA has tended to withdraw from research and technology development with respect to advancing new remote sensing technologies. Hyperspectral sensing is being advanced by the Air Force and radar interferometry by the Canadians. Also, the use of formations of several small, low cost satellites to perform the functions of one large satellite does not appear to have excited much interest in the Agency. All such technology may have significant applications in the economy and society. The transfer of useful technology to the private sector, however, should be through liberal intellectual property rules rather than overt and often unsuccessful "technology transfer" efforts. The private sector always will be better positioned to make business decisions on new technologies than NASA.

Also, one of the major current challenges in both applied and pure science is to create the data handling and processing infrastructure that can make remotely sensed data useful in a timely manner. This is a government-wide and private sector-wide problem and will need a multi-agency approach. For its part, NASA always has had a tendency to fund the collection of data more vigorously than the analysis of the data collected. One little recognized difficulty US policy makers face today is that the major global climate models on which forecasts of global warming are based are founded in the superior, albeit still inadequate, computer systems being used by Canadian and European entities. We are at a significant disadvantage in this regard. Even our competitors, however, cannot model all parameters that clearly are could contribute to climate change. If we wish to leapfrog the systems currently in use by others, and regain control of this important field of modeling science, it will take a significant expenditure of private and/or public funds. NASA probably should be a player in this broader effort. As many of the classes of data used in climate models are collected by NASA or NASA developed satellites, it is conceivable that the Agency should lead such an effort or be closely allied with the NSF, NOAA, and the EPA.

It also should be noted that an attempt is being made in various academic institutions, aided and abetted by environmental activists, to establish "Earth System Science" as a recognized discipline (see the Editorial by John Lawton in the June 15, 2001, *Science*). If this effort begins to show some momentum, NASA's role as a source of objective, remotely sensed data and data trends related to the Earth's surface and its atmosphere may be even more critical in preventing junk science from dominating this new "discipline" and political pressures and litigation derived from it.

Increasing international activity in Earth remote sensing from space has led to increased scientific and administrative coordination of projects between Europe, Japan and the US As these projects produce data that relate to international political issues involving climate, trade, pollution, sovereignty and defense, it is important that NASA, in cooperation with State and DOD, stay competitive technically as well as active in appropriate international organizations.

[The Future for Space Science]

In the future, the above distinctions between pure and applied science probably will remain useful. If, however, the President decides on a major new, deep space initiative at some point, a significant change in emphasis will be in order. In particular, lunar and planetary science, solar physics, and space biomedicine will become much more applied so as to feed directly into the new initiative. [In 2004, this has happened, in part, in response to the President's Moon–Mars Initiative.]

Lunar investigations, for example, may become joint investigations with the private sector and even more oriented toward better understanding of lunar soils, resource distribution, recovery and processing. Lunar resources of immediate interest are Helium-3, Helium-4, Hydrogen, Oxygen, and water, with only Helium-3 having direct applications here on Earth as a fusion fuel. Other resources, however, will have great value for use as consumables in space. Water, for example, can be made anywhere on the Moon by heating the soil to ~800 degrees C., causing solar wind implanted Hydrogen to react with oxides in the soil to produce water. There also is the possibility of water ice at the lunar poles, although not nearly as much or as economically available as many have recently claimed.

Mars investigations, with one significant exception, have developed a base of understanding of the Martian surface that is superior in almost every respect to that in hand prior to the first landing on the Moon by Armstrong and Aldrin. The significant exception relates to the potential of on-going biological activity on Mars. Most scientists knowledgeable about Mars agree that, unlike the Moon, it is possible that simple life forms evolved during the much wetter early history of Mars when conditions were much more Earth-like than today. A major debate, however, rages about whether special water-rich conditions currently exist in the Martian subsurface in which that early life may have persisted up to the present. [In 2004, discoveries through Mars Exploration Rovers have added significantly to our understanding of the role of water on Mars.]

The probability is very small, but still finite, that any life survives in the extremely harsh surface conditions now present on Mars. Because we cannot be absolutely sure there would be no exposure at or near the surface, a human mission to Mars must contend with this uncertainty. It is unlikely that the question of life on Mars and its various nuances will be answered by Mars meteorites or robotic missions prior to a potential human mission, as valuable as such research may be otherwise. Indeed, we probably should not make an unambiguous answer to this question a necessary condition for initiating human exploration of that exciting planet or we may never go! Fortunately, the design and engineering of a human mission to the surface of Mars and its operational planning and procedures can probably eliminate the potential for infection of the crew or the return of infectious agents to Earth. There will be those who would disagree with this statement, however, good solid planning and execution should put any legitimate fears to rest when the time comes to begin. For example, the early crews on the long return flight can run the long-term tests necessary to verify the viability or non-viability of any life forms in a terrestrial environment and, if necessary, leave suspect material in Earth orbit.

Finally, it is important to recognize the close synergy between future development of lunar resources and the technology required to mount an affordable and continuing human exploration and potential settlement of Mars. Some would say we need to test Mars exploration techniques on the Moon, however, this again hardly seems to be a necessary condition before initiating Martian exploration by Americans. Testing on Earth, particularly with respect to issues related to two-way bio-containment, would seem more realistic as Earth is already a biologically rich analog. If we can solve the containment problems here, they surely would be solved for Mars. Rather, an affordable Mars program would be enabled by the private sector's participation in lunar resource harvesting for profit that would require privately funded development of relatively low-cost heavy lift launch vehicles, space habitats with indefinite longevity, low-cost lunar consumables, and space adaptation countermeasures.

NASA's current attempt to fund some development of new technologies for deep space exploration, absent any specific plans for such exploration, is called, unfortunately, Human Exploration and Development of Space (HEDS) Technology Commercialization Initiative or HTCI. This effort, with more name than funding, states that its intent is to pursue new technologies that are valuable for both space exploration and space commercialization and that this is the key to future success in deep space. Without the focus of more specific guidance by the next Administrator or by the President, such an effort has little chance to be productive, particularly when its leadership appears to have never learned the management lessons of Apollo. HTCI management has said that the Apollo Program had a blank check and that was the key to its success. This is incorrect. Although adequate management reserves were available for Apollo as good funding practice always should dictate, there was no blank check. The evolution of strong management systems and managers combined with the extraordinary motivation of young men and women were responsible for Apollo's success [see Sections 9.2 and 9.3].

Further, NASA's HTCI cannot be considered a credible source of space commercialization technology absent definitive private sector involvement in defining what technology should be advanced. When NASA does what it does best, i.e., concentrate on serving the national interest in space and aeronautics, it has been well demonstrated that extensive commercial spinoffs occur. These spinoffs take place naturally without overt efforts to make it happen other than making intelligent choices when alternative approaches exist and providing commercially significant access to its intellectual property. HTCI leadership currently is trying to choose what technologies will be important to future deep space activities in the absence of a coherent set of deep space objectives. For example, development of "self-deploying systems or self-assembling systems" is high on HTCI's agenda without the trade studies necessary to evaluate the cost and reliability of such systems versus human-aided deployment and assembly. HTCI also is emphasizing "solar power and fuel storage" for deep space operations, apparently thinking that there will be commercial spinoffs as well as avoiding the politically sensitive "nuclear" issue. Major deep space operations, however, will require much greater power density than solar and chemical sources can provide, specifically, power systems based on fission or fusion processes. [In 2002, fission research came back on NASA's agenda and has become part of the President's Exploration Initiative.]

If, on the other hand, a new deep space initiative began to take form and if it were decided that the entrepreneurial private sector should lead future acquisition of lunar energy and space consumable resources, then a NASA role in research and technology development that would advance this objective and derive future research benefits from it would make a lot of sense (as it has for Aeronautics). A well-conceived NASA program in this regard also would help build the confidence in the investor community necessary to fund the private sector's initiatives.

The most obvious NASA role in anticipation of future deep space initiatives, of course, would be in the engineering of reliable heavy lift booster technology and probably should be a major part of the Space Launch Initiative. Cost sharing with industry, which seems to be a part of HTCI's philosophy, has not been the best way of implementing NASA initiated research and technology development, the failure of the X-33 program being the latest example. As apparently is now the policy in DOD, cost sharing as a way of doing business probably should be dropped. NASA and industry laboratories should do what each does best with NASA funding activities in its laboratories that both agree are beyond the current reach of the state of the art but which are essential to a successful venture.

10.10 MAJOR RECENT EVENTS

The tragic loss of the Space Shuttle *Columbia* on February 1, 2003, and the subsequent and protracted accident investigation, changed the face of NASA and not all for the good. NASA has become even more risk averse than before, an attitude that does not bode well for the future. For example, a major, ongoing effort to produce a "roadmap" for bioastronautics, that is, human physiology and behavior in space, appears to be motivated by the reduction of risk instead of the enhancement of performance.[14] Further, by not returning to flight immediately after the proximate cause of the *Columbia*'s accident was determined and dealt with, the door was opened to a full inspection and rebuilding of the three remaining Space Shuttles. This allowed every well-meaning engineer and manager to try to eliminate any possibility of being blamed for a future accident, making a return to flight very difficult and tedious. This self-protective reaction to the *Columbia* accident reflects very poorly on the leadership potential of NASA's senior management. The possibility exists that the Space Shuttles will never fly again and that the United States will continue to be dependent on others for human access to space for many years. China's increasingly ambitious human space flight activities serve to underscore this dependence. As of this writing, the Shuttle's return to flight is planned for mid-2005.

President George W. Bush's January 2004 announcement of a new initiative to return to the Moon, go on to Mars and beyond has set NASA on a new course from that inherited in 2001. The Moon and deep space are now in play again. In response, the last NASA Administrator attempted to make some changes, particularly in the Agency's financial accounting system and in the organization and reporting structure of senior management. A new Exploration Office has been established to specifically implement the President's initiative. This office, however, seems to be grossly understaffed with experienced technical designers and managers. It appears to be without the confidence to set out a plan for implementation of the Moon–Mars Initiative and then go to the broader engineering community for refinements and proposals for implementation. Instead, the opposite has happened. The engineering community has been asked to provide the plan through a huge matrix of strategic and tactical "capabilities" working groups while, simultaneously, proposals are been requested for ideas on technologies and approaches necessary to implement a plan that has not yet been formulated.

Time will tell if these and future changes will enable NASA to lead humankind back to the Moon and further into deep space. Unfortunately, initial indications are not good. For example, in addition to the potential difficulties mentioned above, the General Accounting Office has announced that NASA's financial accounting still cannot be audited, in part because each Center uses different accounting systems and standards. Further, many of the personnel in senior management positions are there because they have survived in the bureaucracy and not necessarily because they are the best available for the job. Most seriously, a danger exists that an atmosphere again has been created that is antagonistic to internal debate, an environment that has been deadly for NASA in the past. It now appears that the newest NASA Administrator is moving vigorously to overcome these deficiencies.

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11

INVESTORS: THE BEST APPROACH

11.1 INTRODUCTION

THE comparative analysis in Chapter 8 indicates that a privately financed and managed initiative would be the most efficient and productive approach to returning to the Moon in the foreseeable future. Any large-scale private initiative focused on a Return to the Moon will have as its ultimate aim a return on investment from production and sale of lunar resources and terrestrial power. In addition to helium-3 for fusion power, sales of by-products, such as hydrogen, water, and oxygen to customers in space will add to bottom-line income as well as to investor return. The same can be said of ancillary services based on the existence of a lunar settlement and the new space transportation systems required to establish and service that settlement.

The conclusion from Chapter 8 that supports the cost-effectiveness and efficiency of private initiatives related to lunar resources does not preclude either cooperative technology development with NASA as a partner or the involvement of international investors and employees. Such cooperation and involvement might indeed be desirable, particularly if the current Exploration Initiative leads to NASA being given the authority to match private investments aimed at recovery of lunar hydrogen, oxygen, and water for purchase by NASA. Neither NASA nor international entities, however, can be responsible for projects in the critical path to success of a commercial enterprise. If they were so placed, efficient management and operations would be compromised, milestones would slip, and schedules would stretch, based on the post-Apollo history of NASA and international organizations. As was observed with the Space Shuttle[1] and Space Station[2] programs, development and operational costs would also escalate and the project would flounder or be subject to nationalization and even higher costs.

A number of important premises underpin a private enterprise approach returning to the Moon. These controlling premises are as follows:

1. Initial, near-term returns on investment will come from the development and marketing of fusion technology, the first application of which would be isotope production for positron emission tomography (PET) (Section 11.3.1).
2. The United States government will be a domestic and international advocate of the initiative (Chapter 12).
3. Sustained, net power production by deuterium–helium-3 or by pure helium-3 fusion can be demonstrated within six to eight years (Chapter 5).
4. A commercially viable demonstration of a helium-3 based fusion power plant can be made within about 10 years (Chapter 5).
5. The delivery of the first 100 kg of helium-3 to the first commercial 1000-MWe power plant can be achieved within 15 years with a financial envelope of $15 billion in invested capital (Chapters 4–7).
6. Costs of placing payloads on trajectories to the Moon can be reduced to about $3000 per kilogram (Chapter 4).
7. Helium-3 fuel costs, delivered to a fusion power plant, and the capital and operating costs of such a plant, can be competitive with comparable costs of using steam coal for power generation (Chapter 5).
8. An intense, focused, and well-managed initiative can be created that would be comparable to those that successfully implemented the creation of transcontinental rail transportation, the Suez and Panama Canals, the nuclear navy, the Interstate Highway System, the Trans-Alaska Pipeline, as well as the Apollo–Saturn infrastructure to go to the Moon. Business as usual is not an option.

11.2 COMMERCIAL PRECEDENTS IN SPACE

Since the rise of the nation-state, governments have directly or indirectly sponsored exploration and pioneering of new geographic frontiers with trade, treasure, and perceived national interest being the primary motivators. (With respect to perceived national interests, government-sponsored space exploration has been no exception.) Commercial enterprises, however, have either been integrated into, or closely followed, government-sponsored initiatives. Examples exist, of course, when commercial initiatives preceded governmental efforts with high-value resources providing the primary financial incentives for entrepreneurs to assume the risks of exploration: furs, gold, and various precious metals being primary examples in the history of the United States and many other nations. In modern times, the settlement of new lands has involved the sponsorship and protection, if not the outright subsidization, of governments, with the American West, Australia, and Siberia being clear illustrations. On the other hand, until the nineteenth century, the initiation and financing of technological exploration, with the exception of military technology, had rested primarily in the hands of private individuals and groups.

In contrast to the industrial revolution on Earth, the technological revolution in space, and related to space, has rested on the foundation of scientific and engineering developments initiated by governments. Those early technological foundations, however, have been expanded and enhanced through the expenditure of private capital until the initial "seed" financing by government, as important and catalytic as it may have been, became a minor quantitative factor. Space-based communication satellites constitute the best example of this phenomenon,[3] but the gradual growth of products and services using global positioning satellites and commercially instigated remote-sensing satellites are not far behind. Space tourism may be the next major commercial endeavor to become financially viable, building on the early foundations in technology and human space flight experience provided by government in this "new ocean."

11.2.1 Communications

Arthur C. Clarke's articulation in 1945[4] of the concept of using geosychronous communications satellites for global communications networks provided the intellectual foundation for what has become a multi-billion dollar industry. In 1961, President John Kennedy's speech to Congress offering space-based communications technology to the world became the catalytic event stimulating commercial interest in communications satellites[5] although a great part of the research and experimental foundation for the infant industry was created in the early years of NASA under President Eisenhower.[6] Kennedy's speech was followed by Congressional authorization of the Communications Satellite Corporation (Comsat) in 1962 and then by the signing and ratification of the International Telecommunications Satellite (INTELSAT) agreement in 1964.[7]

Although the major telecommunications companies in the United States were initial investors in Comsat, they quickly began to implement plans for competitive satellite networks to serve long-distance customers. The first truly commercial communications satellite, the Hughes-built Westar satellite, was launched by Western Union in 1974.[8] Today, the competitive marketplace involving communications satellites is extremely dynamic and includes many commercial service providers and satellite design and manufacturing entities throughout the world. This pure space industry related to satellite communications constitutes the fastest growing segment of an information industry with $1.4 trillion in annual revenues.[9]

11.2.2 Other commercial space endeavors

No other pure commercial space activity has arisen since the success of satellite-based communications, although many companies have profitable product lines that rely on the use of satellites deployed by governments. Such subsidized satellites include those that provide global positioning (GPS)[10] and terrestrial remote sensing[11] (such as the GOES weather satellite and Landsat ground-sensing satellite). Additionally, some start-up companies are currently using the United States government as an anchor customer in attempts to create purely commercial, satellite-based space imaging and mobile voice communications systems. The ultimate commercial success of these start-ups has not yet been assured but the potential is great. Finally, proposals currently abound for initiatives in space tourism; however, it is far too soon to determine their ultimate commercial success.

11.3 PHASE I: COMMERCIAL FUSION TECHNOLOGY

The same technologies that potentially will optimize the fusion of deuterium and helium-3 or of helium-3 alone inherently provide small, compact sources of protons, neutrons, or other energy. Applications of these sources to creating products and services that have profitable or potentially profitable positions in the marketplace creates the strong advantage that lunar helium-3 fusion power holds as the economic foundation for a Return to the Moon. It means that a Return to the Moon can rely on the predictability of the private business and financial sectors to plot a path toward deep space rather than having to rely on the political unpredictability of government initiatives and funding.

Competitive technologies currently may hold the market positions potentially open to compact, inherently mobile fusion devices. The business and technical challenge is to rapidly develop fusion-based technologies that offer operational and cost advantages over existing and future competitors in appropriate market sectors. In this way, with properly constructed business plans, investors legitimately can become persuaded that a competitive return on investment exists in bridging businesses lying along the technical path to commercial fusion power.

Bridging businesses assist in meeting the larger objective of creating the technology and business base for lunar helium-3 fusion power in several ways. First, each successful business further extends the foundations of fusion science, technology, and engineering. Second, retained earnings from each successful business provide additional investment capital for the next step in the enterprise as a whole. Third, the principals and future principals of the growing enterprise gain experience in successively more complex business and technical ventures. Finally, each successful business adds credibility in the investing community for fusion technology in general, for helium-3 fusion power in particular, and for advocates of a Return to the Moon.

The business plan for the Fusion Technology Startup Phase of a private lunar helium-3 initiative would consist of the elements given below. They would be completed by the end of the indicated years. Start-up of this plan would follow initial angel financing of about $15 million (financing milestones below are in italics and major milestones are in bold).

Year 0:

- Complete fusion technology start-up business plan available (PET isotope production).
- *$15 million in angel financing committed to near-term, commercial fusion technology development.*

Year 1:

- Hire senior fusion technology management team for near-term business development.
- Establish headquarters for fusion technology application business.

- **Award fusion technology development contract** (probably involves university-based research group).

Year 2:
- **Complete fusion research and technology development for PET isotope production.**
- Initiate regulatory approval process for application of fusion technology to PET isotope production.

Year 3:
- **Demonstrate manufacturing prototype of PET isotope production device and support structure and demonstrate commercial viability.**
- Complete PET fusion technology business plan.
- **Receive regulatory approval for application of fusion technology to PET isotope production.**
- Initiate marketing and sales activity for PET isotope production.
- *Complete $50-million venture financing for PET isotope production, marketing and sales, and product support.*

Year 4:
- Complete long-term fusion technology business plan (neutron activation analysis [explosives and chemical hazard detection], therapeutic and diagnostic isotope production, nuclear waste transmutation, mobile power sources, etc.).
- **Award additional fusion technology development contracts.**
- Initiate process for acquiring regulatory approval and awarding contracts for various long-term fusion technology applications.

Year 5:
- *First returns on investment from PET isotope production business.*
- Senior fusion management team in place for long-term fusion technology development.
- Establish permanent headquarters for Return to the Moon initiative.
- *$175 million in angel and/or venture financing committed to long-term fusion technology development.*
- **Hire senior Return to the Moon management team.**
- Establish initiative's employee stock ownership plan (ESOP).
- Complete preliminary definition of candidate fusion technology approaches (see Section 5.3).
- Contracts awarded for research and technology development related to candidate fusion approaches.
- Initiate conceptual design of commercial helium-3 fusion power plant.

- Complete economic geology study of *in-situ* concentration and distribution of lunar helium-3 and other solar wind volatiles (see Section 6.3).
- Initiate benchmark design of uprated Saturn V (see Section 4.2).
- Initiate conceptual design of lunar resources production architecture and hardware (see Sections 7.1–7.4).
- Complete preliminary lunar helium-3 fusion power business plan.
- **Complete review of initiative's conceptual architecture and place under broad configuration control.**

(Milestone definitions are continued in Section 11.4 below.)

11.3.1 Diagnostic medical isotope production

The first business opportunity for helium-3 fusion lies in production of isotopes for medical diagnostic applications. Production of short-lived radioisotopes for diagnostic procedures has been a rapidly growing business sector for several decades. For example, technicium-99m, produced as a metastable daughter product of the decay of molybdenum-99, remains the most commonly used diagnostic isotope, involved in hundreds of thousands diagnostic procedures each year throughout the world. For procedures in the United States, molybdenum-99 comes from large fission reactors, with Canadian production dominating the current North American marketplace. With a relatively long half-life[12] of six hours and with the Canadian government currently committed to supporting the provision of sufficient technicium-99m for North America, entry into its production does not appear to be a bridging business opportunity at this time. It might become a future market opportunity once initial fusion development is complete.

On the other hand, fluorine-18 is the dominant radioisotope currently used for rapidly growing clinical applications of Positron Emission Tomography (PET) imaging for cancer diagnosis. Fluorine-18 is a short-lived, positron-emitting[13] isotope with a 110-minute half-life. Fluorine-18 is currently produced in many large, fixed cyclotrons distributed around the United States and the world. Limits on the distribution and reliable availability of fluorine-18 suggest that point-of-use production would have a large market, particularly outside major urban areas.

About 110,000 PET diagnostic procedures using the radio-pharmaceutical "fluorine-18 deoxyglucose (FDG)" were performed in the United States in 2001[14] with that number expected to grow by about 73,000 each year for at least the next few years. Even more rapid subsequent growth is expected as the cost savings and accuracy in determining the stage of cancer become broadly recognized.[15] Approval of a growing number of procedures for Medicare and Medicaid insurance reimbursement fuels the expansion of PET use.[16] The initial business opportunity may be to produce or license the production of the devices and consumables necessary for point-of-use production of high-purity fluorine-18. The production of other, less clinically mature positron-emitting isotopes, carbon-11 (20-minute half-life), nitrogen-13 (10-minute half-life), oxygen-15 (2-minute half-life), will also be investigated during the start-up phase of this business. Isotopes with these shorter half-lives can extend the benefits of PET diagnostics to children and pregnant women for whom fluorine-18's residual radiation dose is beyond allowable regulatory limits. The production of nitrogen-13 in an inertial electrostatic confinement (IEC) research device has been demonstrated in the laboratory of Wisconsin's Fusion Technology Institute.[17]

More than 50 dedicated cyclotron particle accelerators served the 2001 US market for fluorine-18.[18] The non-US market is served by more than eight cyclotrons of this type. Due to fluorine-18's short half-life, these large, fixed-site cyclotrons cannot easily serve markets more that about an hour of air travel (~300 miles or 500 km) distant from their location without a large excess production capacity. For a cyclotron-based producer to produce enough fluorine-18 for a single bedside PET scan and then test it, insert it into FDG, and ship it about 300 miles, requires the allocation of over four times the amount actually needed. Thus, the initial target market for point-of-use fusion-based devices will be the more distant, small urban to rural market that is currently not served. Healthcare facilities located away from urban centers with less than about 500,000 population, or not located at a major university research center, normally do not have the potential patient base to financially support the capital costs of a cyclotron production unit. They also require a level of frequency and reliability in supply beyond that provided by air transport. On the other hand, lower capital and production costs should ultimately open the urban, cyclotron-served markets to penetration. In the case of the very short half-lives for carbon-11, nitrogen-13, oxygen-15 , of course, even urban markets can be served by point-of-use production.

Rapid growth is probable from the 2001 fluorine-18 market level of about $75 million. Projected sales of PET scanners indicate that the market can be expected to grow by about $55 million each year for several years. Such projections, however, do not yet include the potential of serving fluorine-18 demand at sites beyond the reach of cyclotron production, where the primary market advantage for fusion technology exists.

Preliminary financial analysis (Table 11.1), limited initially only by a conservative rate of introduction of isotope production devices, indicates that financial breakeven could occur in the third year of post-development business. Revenues of $39 million with a gross margin of 50% are estimated for the third year. Revenues are estimated to be $126 and $302 million with gross margins of 63% and 65% in the fourth and fifth year, respectively. On top of this PET-only market, the combination of PET with computed tomography (CT) is increasingly of interest in medical diagnostics.[19]

TABLE 11.1 Growth of potential fluorine-18 revenues (in $ millions)

Year	1	2	3	4	5
Installations (total in service)	3⁽¹⁾	10	40	130	310
Revenues					
Kit⁽²⁾	0.0⁽³⁾	6.5	39.0	126.75	302.25
Production devices⁽⁴⁾	0.0	0.1	1.05	5.4	15.3
Training⁽⁵⁾	–	0.1	0.3	0.9	1.8
Services⁽⁶⁾	–	0.1	0.4	1.3	3.1
Licensing⁽⁷⁾	–	–	–	15.0	35.0
Total revenues	0.0	6.8	40.75	149.35	357.45
Cost of Sales					
Test and evaluation⁽⁸⁾	0.5	0.5	0.5	0.5	0.5
R&D	1.0	2.0	3.0	4.0	5.0
Installation⁽⁹⁾	0.255	0.625	2.65	8.05	16.60
Kits⁽¹⁰⁾	0.800	3.0	12.0	39.0	93.0
Training⁽¹¹⁾	0.2	0.5	0.5	0.9	2.0
Services⁽¹²⁾	0.55	0.7	0.95	1.25	2.6
Warranties & options⁽¹³⁾	–	–	0.1	0.45	1.35
Licensing⁽¹⁴⁾	–	0.3	0.5	0.5	0.5
Total cost of sales	**3.305**	**7.065**	**20.2**	**54.65**	**121.55**
Gross margin	(negative)	(negative)	50%	63%	65%
EBITDA	**(3.305)**	**(0.265)**	**20.55**	**94.70**	**235.90**

(1) Beta site installations as follows: (a) Site that serves a single academic research institution. (b) Site that serves a single/large clinical practice. (c) Site that serves several clinical locations in a small city.

(2) Each kit can produce three calibrated 10-millicurie doses of fluorine-18 each 24 hours (40% conversion efficiency) at a competitive sale price of $600 per 10-millicurie dose. (This sale price per dose makes no allowance for the cost of shipping by air, now borne by users remote from current cyclotron production. For example, between Phoenix and Albuquerque, that additional cost is ~$180 per dose.[20] In this

particular market, an average of about 10 scans per week are being performed, with a failed shipment of three doses occurring about once every three months, a further increase in cost to the user due to the need for last minute rescheduling.) Revenue assumption is that each installed device produces 1 watt of fusion power and will serve an annual demand of 1000, 10-millicurie doses per year in Year 2 and Year 3 and 1500 doses, subsequently. (Some customers may purchase pairs of devices in order to ease scheduling demands. In the out years, it is assumed that greater than 1 watt fusion power retrofits will be available or users will augment production with the installation of additional devices.)

(3) Assumes that beta sites will use only 200 doses each during the one-year test period at no charge for the first year.

(4) Assumes $0 charge for each beta site installation and for the first seven installations in Year 2 (10 total), $25,000 each for 30 installations in Year 3, $50,000 each for 90 installations in Year 4, and $75,000 each for subsequent installations. Except for beta site installation during the first year, there will be a charge of $10,000 per year for helium-3 and deuterium fuels, subject to annual adjustment based on fuel costs.

(5) Mandatory training charge of $10,000 per installation. Includes training materials, device and kit specifications, operating manual, etc., three days of Internet instructional availability, 16 hours of on-site instruction, and an option for the training of additional operators each year for an additional $5000 each.

(6) Service package charge is $10,000 per year with a five-year warranty on each isotope production device and an option to extend the package and warranty for additional five years after refurbishment or replacement of the device.

(7) Licensing fees estimated at 10% of the annual "production kit" revenues after three years of market development.

(8) Three current production devices will be run full-time in a test environment to ascertain failure modes and effects, component longevity, and diagnostic and malfunction procedures, as well as operational issues and cost-saving opportunities.

(9) Isotope production devices are assumed to cost $75,000 each plus $10,000 each per year for helium-3 and deuterium. This device cost may be high in view of an IEC device for neutron activation analysis was priced at $50,000.[21]

(10) Isotope production kits, with parent isotope included, are assumed to cost $200 per dose when in full production. Beta site kits are assumed to cost $1000 per dose. These numbers are conservative, pending engineering development of the kits.

(11) Salary, benefits, travel and training materials of $200,000 per year for one installer/trainer to handle up to 30 devices per year. Annual costs assume that personnel are hired at least six months before actual need in order to provide familiarization and training and to take care of any lengthy early installations.

(12) Salary, benefits, travel, communications charges, and tool costs of $250,000 per year for one service engineer per 50 installed devices and 200,000 per year for each of three shifts for an "isotope.com" monitor/service dispatcher. Annual costs assume that personnel are hired six months before actual need in order to provide familiarization and training.

(13) Cost of warranties and options is assumed to be 10% of the revenues from the sale of proton producing devices and would include replacement of defective production kits, if any. Five years after each device installation, additional costs will be incurred as a result of refurbishment and replacement of installed devices.

(14) Salary, benefits, travel, communications charges, and legal costs of $300,000 in Year 2 and $500,000 per year subsequently for active marketing and monitoring related to the licensing of intellectual property owned or partly owned by the company.

Technology for the production of fluorine-18 would be based on inertial electrostatic confinement (IEC) fusion technology such as that under development at the University of Wisconsin (Chapter 5). The estimated market price of each device would be about $75,000 as compared to $2.5 million for production cyclotrons.[22] The actual cost of producing a 10-millicurie dose of fluorine-18 in a production device has been calculated to be between $16 and $17, including the cost of helium-3, deuterium, oxygen-18, electricity, cost of capital, maintenance, and equipment (see Table 11.2).

TABLE 11.2 Estimated cost breakdown for production of one 10-millicurie dose of flourine-18 (in dollars)

Cost item	Amount used	Cost ($/10-mCi ^{18}F)
Helium-3(1)	3×10^{-8} g	<0.01
Deuterium(2)	2×10^{-8} g	<0.01
Oxygen-18(3)	2×10^{-8} g	<0.01
Electricity(4)	60 kW/hr	3.00
Equipment(5)	N/A	10.00
Maintenance(6)	N/A	2.66
Capital(7)	N/A	<1.00
Total(8)	**N/A**	**16.66**

(1) Helium-3 ~$1000/g (2004)
(2) Deuterium ~$440/kg (2004)
(3) Oxygen-18 estimated as ~$440/kg (same as deuterium).
(4) 10 kW for 6 hr at $0.05/kWhr with production efficiency (Q) = ~10^{-4}
(5) $75,000 amortized for 1500 doses/yr over five years.
(6) $10,000 amortized for 1500 doses/yr over five years.
(7) Estimated $20m at 10% interest spread over 60,000 doses in Year 3.
(8) Leakage of all input gases by factor of 10^3 would increase production cost by ~$0.03.

With respect to financing, it is expected that start-up development would require about $12 million that would be provide by an "angel investor," that is, someone who is interested in high-risk, high-return investments that are beyond the risk-taking potential of venture capitalists. Primary start-up development objectives (Table 11.3) are: (1) a manufacturing prototype of an IEC fusion source of protons[23] producing 1 watt of fusion power; (2) a manufacturing prototype of an isotope production kit for fluorine-18; (3) a post-development business plan to support second round financing; (4) a prototype Internet-based sales, training, and equipment diagnostics and maintenance system; and (5) recruitment of senior management with specific business and technical

TABLE 11.3 Three year breakdown of a start-up development budget for PET isotopes production (in $ millions)

Objective	Year		
	First	Second	Third
1. Proton-generating IEC device	0.39	0.40	3.86
2. Isotope production kit	0.10	0.10	0.50
3. Post-development business plan	0.15	0.15	1.35
4. CAD/CAM models	0.10	0.10	0.20
5. Internet sales and services development	0.10	0.10	0.20
6. Internet training development	0.10	0.10	0.20
Project management	0.10	0.40	1.05
Contingency (~20%)	0.20	0.27	1.30
Total	**1.24**	**1.62**	**9.14**

experience in the diagnostic medical marketplace. Once start-up development is complete, the project should be of interest to venture capitalists or to additional private investors.

It also should be noted that extremely detailed diagnostic lung imaging is possible through direct sensing of inhaled helium-3.[24] Helium-3 can be polarized and magnetic resonance imaging (MRI) scanners can track the polarized gas as it moves in the lungs. The potential demand to use helium-3 for this purpose has not been determined, but it could be high if this diagnostic technique becomes broadly available.

11.3.2 Neutron diagnostic imaging

Recent experiments at Duke University Medical Center suggest that neutron activation of elements concentrated in tumors or in pre-tumor cells can be used in diagnostic gamma-ray imaging.[25] Deuterium–deuterium fusion production of neutrons in small IEC devices may provide low-cost, point-of-use neutron beams for this purpose.

11.3.3 Therapeutic medical isotope production

A number of other isotopes have therapeutic or diagnostic medical applications,[26] but the Department of Energy's ability to provide reliable and consistent supplies in the United States has been marginal.[27] These isotopes need to be examined relative to future production and long-term sales potential. They are listed below[28] relative to market and current status:

1. Isotopes that have demonstrated proven clinical efficacy but face supply and cost concerns: ^{90}Y, ^{99}Mo, ^{111}In, ^{123}I, ^{99m}Tc and ^{186}Re. These isotopes could dramatically affect the practice of nuclear medicine.
2. Isotopes whose high prices and lack of availability are inhibiting their development toward clinical applications: ^{32}P, ^{81m}Kr, ^{89}Sr, ^{103}Pd, ^{117m}Sn, ^{127}Xe, ^{125}I, ^{131}I, ^{38}K, and ^{153}Sm.
3. Isotopes that show promise as diagnostic and therapeutic materials: ^{15}O, ^{47}Sc, ^{62}Zn, ^{64}Cu, ^{67}Cu, ^{68}Ge, ^{153}Gd, ^{168}Ho, ^{177}Lu, ^{188}Re, ^{211}At, ^{212}Bi, ^{213}Bi, and ^{223}Ra. These isotopes are not currently being investigated because of a lack of availability or high price.

Of particular early interest in this list will be short-lived isotopes: oxygen-15 (half-life (h.l.) 2 minutes), potassium-38 (h.l. 7.6 minutes), carbon-11 (h.l. 20 minutes), copper-64 (h.l. 13 hours), and indium-111 (h.l. 67 hours), that, for example, may have diagnostic or therapeutic applications lending themselves to point-of-use or near point-of-use production in IEC fusion devices.

The current world market for medical isotopes in general, *not* including fluorine-18, has an estimated value in 2000 of about $100 million.[29] The market for other diagnostic imaging isotopes, primarily technetium-99m, has been expected to grow to between $82 and 121 million by 2005.[30] Another estimate of the total market in 1996, however, places it at $116 million, including fluorine-18, with a 10% growth (±7–16%) giving $1.141 billion in 2020.[31] These estimates are inconsistent with estimates of the current fluorine-18 market alone being $75 million based on the number of clinical PET procedures in 1999. On the other hand, newer estimates have the world market in 1998 as already at “an established $1 billion,”[32] a number that includes value added costs. (The non-fluorine-18 market is served in the US largely by production facilities operated by the Department of Energy. Additional production also is anticipated from privatized accelerator facilities in Texas built for the now cancelled Superconducting Super Collider.)

A French view of the 1998 global market for positron emitting isotopes provides a slightly different perspective[33] that is also not consistent with the total market estimates given above. This study reports that the main positron emitting radioisotopes in use are ^{18}F (90% of the market) and ^{11}C, ^{13}N, and ^{15}O (10%). Roughly 150 PET centers operate in the world using ~200 PET cameras (scanners). The annual positron emitting isotope market of ~ $75 million is growing at about 15% per year. (This French estimate of $75 million is a significant fraction of the $116 million given above for 1996 and independently consistent with the estimate used for producing Table 11.1.) Approximately 7% of the sites produce their own radioisotopes; the other 30% come from three sites in Germany and 10 in the US. The study indicates that there are 130 cyclotrons (47 in the US), mostly owned by "public entities," dedicated to supplying positron emitting isotopes for PET[34] with 10 to 15 more cyclotrons being brought on line each year.[35] Each new cyclotron requires about three years to be commissioned.[36]

11.3.4 Detection of landmines and other threats

Portable particle generators for neutron activation analysis could be a near-term derivative of an isotope production device using the deuterium–deuterium fusion reaction.[37] These units would have potential applications in remote or hazardous security operations, such as landmine detection, baggage screening, and terrorist weapons characterization. This possible early opportunity for revenues should be analyzed in the context of the status of potential commercial offerings of IEC-based neutron generators. Significant research and testing of devices for landmine detection is underway in both the United States and Japan.[38]

11.3.5 Nuclear materials disposal (transmutation)

Besides the well-known political obstacles, the primary technical difficulty facing the near-term expansion of nuclear fission power for badly needed, clean electricity production lies in finding a solution to the problem of disposing of highly radioactive fission waste. The United States Department of Energy's current plans are to bury existing waste in a facility deep within the geological formations of Yucca Mountain in Nevada.[39] Legal and political roadblocks continue to sprout up, egged on by debates about the geological stability of the site over the next 70,000 to 100,000 years.[40] In addition, the capacity of this site is insufficient to handle any significant expansion of fission power or of possible deuterium–tritium fusion plant waste in the distant future. A return to the recycling of spent fuel rods from commercial fission plants to recover their unused energy and other useful by-products, and to reduce the volume of actual waste, would solve this problem of capacity. A move back to a recycling strategy, however, does not appear likely in the foreseeable future. Also, future fission plant design, Generation IV, could include the continuous elimination (transmutation) of 90% of what is now considered nuclear waste.[41]

The transmutation of existing fission waste using nuclear processes to eliminate a long-term disposal problem has received modest theoretical and experimental attention. Use of the intense flux of protons that future deuterium–helium-3 fusion reactors could deliver provides one possible approach to transmutation. Various stable and short-lived isotopes can be produced by transmutation with protons. Engineering design of a process that efficiently exposes waste products to such a proton flux will be challenging, however. The nuclear power industry, on the other hand, should consider exploring this approach if only to have a backup option should the government be unable to deliver on deep burial – a failure that would eventually remove this important power system from the list of national options.

11.3.6 Mobile power sources

Once sustained ignition of pure helium-3 fusion power is demonstrated (see Section 11.4 below) – that is, power with no secondary radioactivity from deuterium neutron production – the potential exists for the development of mobile sources of efficient electrical power. There are a number of possible applications of such sources, including electrically powered large aircraft, various land and sea transportation systems, space defense applications, and remote site base-load power plants. Consideration of these potential business opportunities will begin once pure helium-3 fusion ignition is demonstrated, potentially as early as Year 7 in the milestone scenario given below. This timing will depend on how rapidly pure helium-3 fusion can replace deuterium–helium-3 fusion in the technology development program.

11.4 PHASE II: FUSION POWER DEMONSTRATION

By the end of the first phase of a lunar helium-3 fusion power initiative, earnings from one or more fusion technology ventures should be supporting increasing levels of research and technology development related directly to fusion power, space access, and resource production. In addition to the use of retained earnings, and possibly of debt financing tied to the initiative's equity interests in fusion technology businesses, angel investors will continue to be sought to support the Fusion Technology Development and Manufacturing Phase of the business plan. Continued development success as well as earlier successes in fusion technology applications should attract the interest of investors.

The second phase of a private lunar helium-3 initiative would consist of the elements given below during Years 6 through 10.

Year 6:

- Establishment of an implementing fusion development center with transfer of appropriate design and development responsibilities.
- Selection of the top two technical approaches for commercial helium-3 fusion reactor development.
- Complete the conceptual design of a commercial helium-3 fusion power plant (except for inclusion of final technical approach to a fusion reactor).
- Select the first pool of lunar astronauts and settlers for participation in design, test, and manufacturing activities as well as eventual lunar settlement activation.
- Complete the evaluation of alternative heavy booster concepts as compared with the Saturn VI benchmark.
- **Complete the business plan for a lunar helium-3 fusion power initiative**.

Year 7:

- **Achieve sustained helium-3 fusion ignition by one or more technical approaches.**
- Complete the selection of prime technical approach to commercial helium-3 fusion power.
- Complete the conceptual design of a helium-3 fusion reactor and integrate that design into the conceptual design of power plant.
- Complete the conceptual design of the Saturn VI or an alternative booster.
- Complete the conceptual designs of the lunar production architecture and hardware.
- *Complete a $500-million initial Phase II angel and/or venture capital financing.*

Year 8:

- Complete the preliminary design of a commercial helium-3 fusion power plant and establish configuration control.
- Complete the final design of a demonstration plant for commercial helium-3 fusion.
- **Initiate the construction of a helium-3 fusion power demonstration plant.**
- **Establish implementing development centers for launch vehicles and for lunar production systems with the transfer of appropriate design and development responsibilities.**

Year 9:

- Complete the construction of a helium-3 fusion power demonstration plant.

- **Demonstrate the successful operation of a helium-3 fusion power plant to establish its commercial viability.**

Year 10:

- *Complete a $5-billion final Phase II venture capital and/or public equity financing.*
- **Select personnel who will activate the first lunar resource production site and settlement.**
- Complete the preliminary design of the Saturn VI or an alternative heavy booster and establish configuration control.
- Initiate preliminary design of a launch site for a Saturn VI or alternative heavy booster.
- Complete the preliminary design of the lunar production architecture and hardware and establish configuration control.
- Initiate the design of a production and settlement operations center at the lunar production center.
- Initiate marketing and sales for helium-3 fusion power plants.

The total financing required for the above activities has been estimated to be about $3 billion for fusion power, $2 billion for the Saturn VI, and $0.5 billion for lunar production. Success in meeting the indicated milestones will depend on timely completion of various financing efforts.

11.5 PHASE III: SATURN VI AND LUNAR PRODUCTION

With successful demonstration of the commercial viability of helium-3 fusion power in Phase II, financing for the lunar aspects of the initiative should be available. Thus, Phase III of a private lunar helium-3 initiative would have the following elements during years 11 through 20.

Year 11:

- Complete the final design of the Saturn VI or an alternative heavy booster.
- **Sign manufacturing contracts for a heavy booster.**
- Select a heavy booster launch site.
- Complete the design of a heavy booster launch site.
- Initiate the construction of a heavy booster launch site.
- Complete the final design of lunar production architecture and hardware.
- Sign manufacturing contracts for lunar hardware.

- Submit preliminary applications for launch, payload return, and other necessary operational licenses.
- Complete the design of lunar production and settlement operations center.
- Initiate the construction of an operations center.

Year 12:
- *Complete a $7.0-billion Phase III public equity financing.*
- Complete the component and system level testing of a heavy booster.
- Complete the component and system level testing of lunar hardware.
- Complete the construction of a production and settlement control center.
- Complete the construction of a heavy booster launch site.
- Complete the mine and settlement architecture and the planning for its emplacement.
- Submit the final applications for launch, payload return, and other necessary operational licenses.

Year 13:
- Receive launch, payload return, and other necessary operational licenses.
- **Full system test launch of a heavy booster.**
- Complete the full system tests of lunar hardware.
- **First activation launch for the lunar resource production settlement.**
- **Establish the lunar production center and settlement on the Moon.**

Year 14:
- **First shipment of 100 kg of lunar helium-3 received at first 1000-MWe fusion power plant.**
- Begin the organization of ancillary space businesses.
- Establish on-call, asteroid deflection capability.

Year 15:
- **First shipment of hydrogen, oxygen, and water to a space customer.**
- Sign a contract to support development of a human mission to Mars.
- **First tourist flight to the Moon.**

Year 16:
- **Scientists return to the Moon and establish permanent laboratory/observatory.**

Year 17:
- **Organize International Environment and Energy Foundation.**

Year 18:
- **Launch the first human mission to Mars.**

Year 19:
- **Achieve financial breakeven for lunar helium-3 production and for helium-3 power generation.**
- Pay first dividend to shareholders.
- Provide initial funding for the International Environmental and Energy Foundation.

Year 20:
- **First human landing on Mars.**

To gain overall perspective, the following outline summarizes the major financial and programatic milestones given above for the first 20 years of a commercial lunar helium-3 fusion power initiative:

Year 0:
- *$15 million in angel financing committed to near-term, commercial fusion technology development.*

Year 1:
- **Award fusion technology development contract.**

Year 2:
- **Complete fusion research and technology development for PET isotope production.**

Year 3:
- **Demonstrate manufacturing prototype of PET isotope production device and support structure and demonstrate commercial viability.**
- **Receive regulatory approval for application of fusion technology to PET isotope production.**
- *Complete $50-million venture financing for PET isotope production, marketing and sales, and product support.*

Year 4:
- **Award additional fusion technology development contracts.**

Year 5:
- *First returns on investment from PET isotope production business.*

- *$175 million in angel and/or venture financing committed to long-term fusion technology development.*
- **Hire senior Return to the Moon management team.**
- **Complete review of initiative's conceptual architecture and place under broad configuration control.**

Year 6:

- **Complete the business plan for a lunar helium-3 fusion power initiative**.

Year 7:

- **Achieve sustained helium-3 fusion ignition by one or more technical approaches.**
- *Complete a $500-million initial Phase II angel and/or venture capital financing.*

Year 8:

- **Initiate the construction of a helium-3 fusion power demonstration plant.**
- **Establish implementing development centers for launch vehicles and for lunar production systems**

Year 9:

- **Demonstrate the successful operation of a helium-3 fusion power plant to establish its commercial viability.**

Year 10:

- *Complete a $5-billion final Phase II venture capital and/or public equity financing.*
- **Select personnel who will activate the first lunar resource production site and settlement.**

Year 11:

- **Sign manufacturing contracts for a heavy booster.**

Year 12:

- *Complete a $7.0-billion Phase III public equity financing.*

Year 13:

- **Full system test launch of a heavy booster.**
- **First activation launch for the lunar resource production settlement.**
- **Establish the lunar production center and settlement on the Moon.**

Year 14:

- **First shipment of 100 kg of lunar helium-3 received at first 1000-MWe fusion power plant.**

Year 15:

- **First shipment of hydrogen, oxygen, and water to a space customer.**
- **First tourist flight to the Moon.**

Year 16:

- **Scientists return to the Moon and establish permanent laboratory/observatory.**

Year 17:

- **Organize International Environment and Energy Foundation.**

Year 18:

- **Launch the first human mission to Mars.**

Year 19:

- **Achieve financial breakeven for lunar helium-3 production and for helium-3 power generation.**

Year 20:

- **First human landing on Mars.**

11.6 MANAGEMENT STRUCTURE

Observations of large and successful management organizations, compared to those that stagnate or fail, as well as lessons from NASA's successes and failures in space-related projects, indicate that a balance must be achieved between three overriding factors if a large, deep space initiative is to be successful. Assuming that a tough, competent, and disciplined senior management team is in place, these core factors are delegation of responsibility, senior level oversight, and coordinated decision-making. Delegate responsibility to *too few* others and upper management becomes saturated as well as too knowledge-deficient to exert competent senior level oversight. Delegate to *too many* others and coordinated decision making requires too many interactions to be efficient. Generally, it appears that balance is best attained if each senior manager oversees no more than five subordinate management positions. This Hierarchy of Five reporting and decision-making balance was that originally envisioned by the drafters of the Constitution of the United States, later to be temporarily revived by President Ronald Reagan. It also is the balance that is recommended here. The addition of just one more subordinate position increases the probable interactions required to evaluate a potential decision from 32 to 64 (2^n). Success, however, will ultimately be determined by having people with the right experience and managerial talent filling each position in the organization chart.

Although the discussion that follows will be directed toward a private initiative to Return to the Moon, the basic structure and functions would be applicable to a restructured, NASA-led effort or to any management scheme that hopes to succeed. The "CEO" in the case of NASA would be the "Administrator" and the Board of Directors would be the cognizant White House personnel and Congressional oversight and appropriations committees. This topic has been covered more fully in Chapters 9 and 10.

11.6.1 Organization

The organizational structure of a private initiative to Return to the Moon determines many of the selection criteria to be applied in the hiring of senior management. This structure also establishes the roles and missions and the lines of authority and coordination that senior management will be expected to follow. The organization will need to combine the most efficient corporate systems to a working environment that fosters technical innovation and managerial initiative. Toughness, discipline, and competence will be the watchwords for both engineers and managers. Figures 11.1 and 11.2 illustrate a logical and time-tested organizational structure and the responsibilities implied by each position in that structure.

Corporate governance will rest in a Board of Directors (BOD) who are responsible to the initiative's investors for the hiring of the Chief Executive Officer (CEO) and for assisting in the hiring of the senior managerial team. Ultimate responsibility for success or failure rests with the Board and all candidate directors should understand this very clearly before agreeing to serve. In most circumstances, the Chair of the Board should be independent – that is, not a part of senior management. The Board also must oversee strategic planning, management succession planning, financial reporting and controls, and employee compensation and benefits. These oversight functions should be clearly spelled out in the charters of the formal committees for Strategy, Governance, Audit and Finance, and Human Resources, respectively, where detailed discussions with appropriate members of management occur no less than quarterly. Large companies, as this initiative ultimately will be, function best with Boards composed of 12 to 15 directors with diverse but relevant experience. No

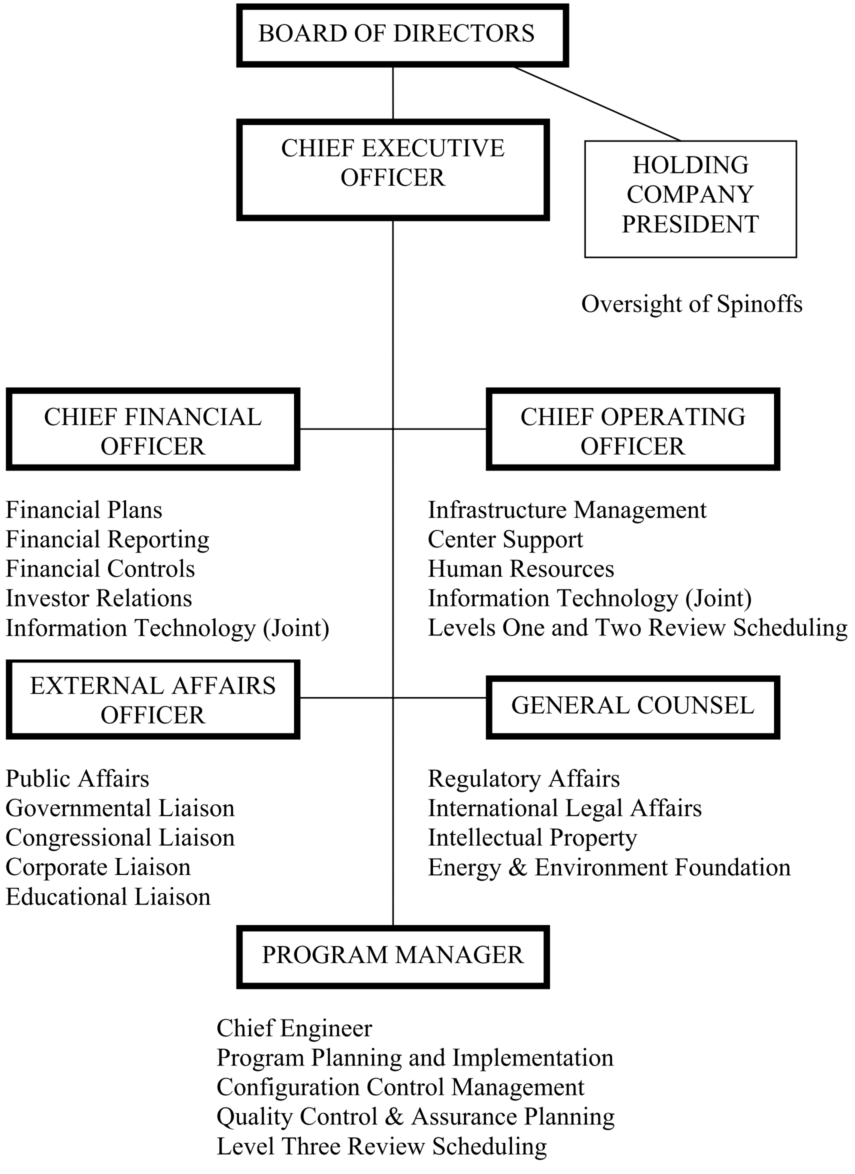

FIGURE 11.1 Organizational structure and primary responsibilities for a private initiative's senior management at Levels One and Two.

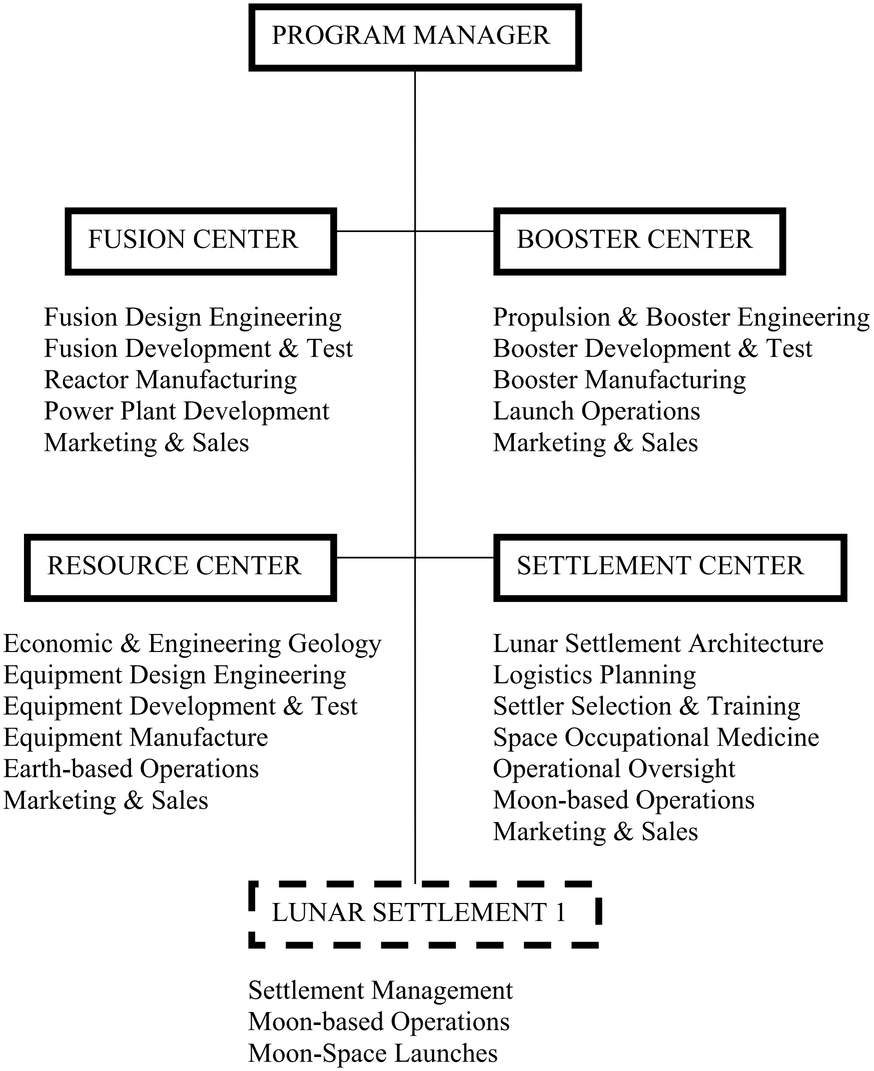

FIGURE 11.2 Organization structure and implementation center responsibilities (Level Three) that would lie under a private initiative's Program Manager.

more than two directors should be members of management: the CEO, and, because of the critical role of continued investor financing to this particular enterprise, the Chief Financial Officer (CFO). As will be discussed below, a special case for Board membership can be made for the President of the Holding Company that oversees the initiative's investments in spinoff companies.

Directors should collectively have experience and knowledge in technical, scientific, financial, and managerial fields that relate to the interests of the initiative. Some members of the Board should have backgrounds to assist in governance of the Holding Company where investments in spinoff companies are managed. The Board will select the President of the Holding Company. Board fees should be at a level that compensates for a commitment of time commensurate with the needs and growth of the initiative and the level of legal and financial liability that attaches to modern corporate Board membership.

The Chief Executive Officer's shoulders carry most of the weight of success or failure for the initiative. The CEO is the primary planner, manager, and inspirational leader. By background, experience, and personality, the CEO must be capable of conducting the most senior level (Level One) oversight of all elements of the initiative that require formal review and approval. Level One oversight by the CEO would include periodic reviews of program status, special reviews prior to significant changes in program direction, event reviews prior to major operational commitments, and annual reviews of the initiative's long-range strategic and financial plans. The ideal CEO would have a PhD in aerospace-related engineering, a clear entrepreneurial bent, a record of successful engineering and corporate management of large complex companies, and a clear ability to inspire dedicated performance by others.

The second level of corporate management will consist of the Chief Financial Officer (CFO), the Chief Operating Officer (COO), the Program Manager, the External Affairs Officer (EAO), and the General Counsel. The major responsibilities for these five positions are indicated in Figure 11.1. Jointly, they will be responsible for Level Two oversight reviews.

The Program Manager clearly will be the senior manager most intimately responsible for implementing the initiative's plans to Return to the Moon and to provide the investor and human benefits of doing so. Implementation will be accomplished through research, development, acquisition, and operational centers dedicated to Fusion, Boosters, Resources, and Settlement with responsibilities as shown in Figure 11.2. The Program Manager, with the participation of all Center

Directors, will coordinate Level Three oversight. The Program Manager, therefore, must find very special people, each with very broad managerial experience and technical background, to be directors of each of these centers. In addition, the Program Manager will insure that the centers have organized and coordinated their configuration control systems, the internal quality control and assurance systems, and the scheduling of Level Three oversight reviews. Where interfaces exist between the responsibilities of various centers, the Program Manager will make sure that there is joint participation in Level Three oversight reviews.

At all levels of oversight specified above, presentations at formal milestone reviews should be made by the systems managers most directly responsible for technical success. Prior to these reviews, if teams are unable to reach resolution on a critical technical or operational issue, the formal expression of dissenting opinion will be encouraged, but not to the degree that it undermines the ability of managers to manage. If another dynamic and highly motivating program was any indication, namely Apollo, dissenting opinions are quickly addressed and resolved or, if shown to be the superior approach, adopted by the team.

11.6.2 Internal financial and technical controls

Corporate internal controls of financial activities, technical design, and quality assurance require varying degrees of formality and intrinsic commitment. Formal financial controls will be established by a combination of "best practices" and the requirements of law and regulation, not always one and the same. The CFO will be responsible for creating the necessary financial control system and its documentation, establishing corporation-wide training in its application, and cooperating in periodic audits of control and regulatory compliance.

Compliance with approved technical designs and mission architectures, that is, "configuration control," will be established after the preliminary design review (PDR) for each system, system of systems, and implementation planning segment. Center level configuration control boards (CCBs) will be responsible for assuring design compliance and for coordinating review and acceptance of any design changes. The CCBs also will monitor conceptional designs after the conceptional design acceptance review (CDAR) milestone has been reached for major hardware and software systems and for integration plans related to the operation of these systems. A sub-board of each CCB will oversee the development and configuration control of all ground support software and that software's compatibility throughout the initiative.

Finally, quality assurance and control (QA&QC) only can be treated as the responsibility of every employee, every contractor employee, and every subcontractor employee. The acceptance of this responsibility must be guaranteed through the continuous efforts of management, technical managers, and flight personnel. In addition to emotional ownership, each company employee also must have financial ownership in the success of the enterprise through employee stock ownership plans (ESOPs). Stock ownership by contractor and subcontractor employees also should be facilitated and encouraged.

11.6.3 Modern management techniques

There is no foreseeable substitute for intuitive insight and common sense in the management of a project to Return to the Moon. Over the past 30 years, however, the continued maturation of computer technology has created new techniques for managing complex development projects. The potential for modeling complex management, financial and operational interactions,[42] designing expert systems and management simulations,[43] mining data-bases, and storing and selectively retrieving large amounts of information has expanded almost beyond the imagination of those of us active during Apollo. As a private initiative grows and matures, these modern management techniques will need to be examined and the best available chosen for implementation.

11.6.4 Personnel

The best organizational structure that might be devised to accomplish a major initiative such as a Return to the Moon will fail if its personnel are not those needed to make it work. (The rate and timing of personnel hiring, of course, will be determine by having met the investment targets given in the above milestones.) In addition to filling the senior positions indicated in Figures 11.1 and 11.2 with experienced and managerially competent men and women, hiring will focus on recent university and college graduates as well as young immigrants from other countries. Emphasis on youth is necessary because of the critical role played by imagination, stamina, and motivation in the planning, design, development and test phases of an initiative of the scale envisioned in a Return to the Moon. Most of the detailed responsibility for success will lie with these young engineers, technicians, scientists, accountants, staff assistants, and secretaries, hired and managed by mid-level managers selected in-turn by the Center Directors discussed above. The availability of youthful personnel for subsequent hires will depend in part on the initiative's support of research and other educational activities at relevant academic and research institutions as well as basic math and science education in elementary and secondary schools.

Mid-level managers with 10 to 15 years' experience will need to be hired by center directors to channel youthful energy into productive work. These managers will be selected as much for their educational and development skills as for their managerial and mentoring records. The best of their "students" will be needed as future managers as the initiative grows. As discussed in Section 9.2.3, a traditional set of professional values underpinned the men and women of Apollo. Replicating this focus on professional values by the generation that returns to the Moon would contribute greatly, and may be essential, to its success.

In addition to competitive industry salaries, the initiative's personnel would benefit from employee stock ownership plans (ESOPs) and many may have the opportunity to be selected as lunar settlers. The initiative's personnel should be eligible and, if fully qualified, may be selected preferentially for permanent transfer to the Settlement Center on the Moon. It can be expected that a viable initiative to Return to the Moon, as well as for the development of fusion power, will attract applications for employment from many highly motivated people with the pioneering spirit of their ancestors.

Much of the research and technology development work overseen by the Centers will be contracted out to qualified university and college-based research groups or to emerging small businesses. Clearly, areas of particular expertise and experience in large, established businesses will be tapped as necessary. The personnel of these entities will be as important to success as those of the initiative itself. In the case of academically centered research and technology development, the initiative will tap the energy of students as well as the experience and intellect of their professors. The students involved in these activities will form a critically important pool of future employees. The primary challenge in this regard will be to instill a higher level of urgency to academic work than is normally the case. To encourage academic excellence and build for the future, it is likely that a phased scholarship program, with performance incentives to continue, will be instituted, beginning with top high school graduates going to selected colleges and universities that have strong math, science, and engineering programs.

In the case of emerging and qualified small businesses, they will become part of the permanent manufacturing base required by the initiative. Their early exposure to competent contract and subcontract management and quality control will foster later successful product delivery and performance.

11.6.5 Launch and space operations

A launch operations complex, managed within the Booster Center, will conduct Earth to Moon launch activities. Experience during the Apollo Program indicates strongly that this separation of launch operations from in-flight and lunar operations is both a workable and a low-risk way of dividing responsibilities, each of which demands intense concentration by personnel of different training and experience. Similarly, early in-flight and lunar operations will be managed by a flight operations center within the Settlement Center. The extraordinarily successful Apollo model[44] for launch and mission operations clearly would be an appropriate guide in the organization of these start-up operational activities (see Chapter 9).

Initially, a lunar settlement will depend almost entirely on supplies and equipment imported from Earth. The only lunar resources that can be used immediately are solar energy for power and regolith for radiation protection and road aggregate. As discussed in Chapter 6, when an initial helium-3 production capability exists, hydrogen and water will also be available. With water and electrical power, oxygen can be produced and some food production can begin as soon as agricultural shelters have been constructed. The settlement, however, will need imports of new hardware and replacement parts. Imports of replacement parts will be reduced to the degree that repair and refurbishment can be implemented at the settlement. Eventually, the demand for repair and refurbishment of parts will increase to the level where additional personnel will be required for this function. Once food production starts, food imports will be reduced to necessary and desired foods that are not compatible with early lunar agriculture.

Once the settlement is well established on the Moon, primary responsibilities for all lunar surface operations should be transferred to settlement personnel. From the aspect of ease of communications as well as other cost-saving factors, such a transfer will make both practical and financial sense. Indeed, the lunar settlement will become a fifth management center in the overall organization (see Figure 11.2). Close coordination between all the initiative's centers, however, will clearly continue to be required. For example, settlement operations would particularly need assistance in organizing long-term logistics and in the planning of Earth and Moon launch manifests.

11.7 ANCILLARY BUSINESSES

An additionally exciting aspect of a successful private initiative for a Return to the Moon and the development of helium-3 fusion power lies in ancillary space and terrestrial business services, marketed to a variety of customers. As discussed in more detail in Section 10.5, two historical types of potential commercial activity related to space can be defined. First, there are those activities that represent an expansion and improvement on services with broad existing commercial foundations. The most obvious of these services has been the explosion in satellite communications services since their introduction in the 1960s, when satellite communications were built primarily on an existing infrastructure and funded by the United States government under the Eisenhower and subsequent Administrations.[45] The use of satellites blended into the existing communications infrastructure with great added value. Second, potential commercial activity in space may offer a type of service, such as terrestrial remote sensing, with few or any existing commercial foundations. This constitutes a much more difficult market challenge.

Half a dozen of the assets developed for the lunar helium-3 fusion initiative would make the offer of ancillary services possible. Those assets are:

1. **Heavy lift rockets capable of placing 50–100 metric tonnes on an escape velocity from the Earth (250–500 tonnes into Earth orbit)**. Commercial, scientific, and national defense applications of large Earth-orbit satellites or satellite constellations and of space planes could be considered if this capability were available at costs a factor of 10 below what is possible today using existing launch vehicles. Possibly the most important long-term application of this capability will be the on-call protection against the impact of large asteroids or comets on the Earth.
2. **Low-cost space lift services at about $3000/kg to the Moon and to deep space (about $600/kg to low Earth orbit)**. This "cost," of course, would not necessarily be the "market price" quoted to external customers for ancillary launch services. These costs are a factor of 10 less than that quoted by existing suppliers of relatively large rockets (~30,000 kg to low Earth orbit, ~6000 kg to the Moon).
3. **Permanent lunar facilities and support for further lunar exploration, Moon-based astronomy, and tourism**. Lunar exploration can resolve many issues that remain to be resolved about the origin and evolution of the Moon and its relationship to Earth, Mars, and other terrestrial planets. Further, astronomy can benefit

from the "radio interference free zone" of the night-time lunar far-side which interests radio astronomers, as does the long-term viewing opportunity at the lunar poles. Finally, lunar tourism is, of course, a dream of many.

The added cost of supporting such functions would be a relatively small addition to the sustaining expense of normal launch and settlement activities. A reasonable profit margin added to these costs would leave the expense of conducing a variety of lunar science and exploration efforts far below that which would be required if funded independently. In fact, major lunar-based science and exploration may not be financially feasible in the foreseeable future unless low-cost launch and lunar infrastructure exist for other reasons.

4. **Low-cost lunar supplies of space consumables, including hydrogen, water, oxygen, helium, carbon, carbon compounds, nitrogen, nitrogen compounds, and eventually food**.[46] The value of lunar commodities to customers in Earth orbit, including those assembling a spacecraft to go to Mars, would be less than $600/kg, that is, a market price less than the target cost for payloads launched from Earth by a new Saturn-class booster. These commodities would be by-products of lunar helium-3 production. Their cost would be largely that of launching against the one-sixth Earth gravity on the Moon in contrast to the much higher cost of launching from the Earth.
5. **Helium-3 fusion power plants, approximately 100 MWe, or larger, for use on Earth or in space**. Once commercial helium-3 and/or deuterium–helium-3 fusion power plants have been demonstrated, many applications of relative small versions of these plants will exist. Included in these applications will be remote terrestrial and space electrical power, various defense applications, power for air and ship transportation systems, and mitigation of the effects of climate change such as more extreme heat or cold and rising or falling sea levels.
6. **Helium-3 fusion rocket propulsion systems for use in space, based on fusion power technology**.[47] The technology required to accomplish helium-3 fusion on Earth is also applicable to interplanetary rockets. In order to reduce exposure to long periods of space adaptation and space radiation, such continuously available acceleration and deceleration will be very desirable. Also, the use of rocket systems to deflect asteroids or comets appears to be a better means of protecting the planet than attempting to break up such threatening objects explosively.

Each of these applications and potential customers relative to the initiatives assets is summarized in Table 11.4.

TABLE 11.4 Potential ancillary service areas and profit centers, in addition to medical isotopes production, derived from the technology base and assets required to support lunar helium-3 fusion power plants

		Profit centers					
Service area	Customer	Heavy lift	Low-cost lift	Lunar facilities	Lunar supplies	Fusion power plant	Fusion rockets
Space impact threat protection	Gov't	×					×
* National security applications	Gov't	×	×			×	×
* Space tourism support	Private person or group		×	×			
* Corporate space activities	Public and private companies		×				
* Lunar-based science	Gov't or academia	×	×	×	×		
* Mars exploration initiation	Gov't or academia	×	×	×	×	×	×
* Space station supply	Gov't or corporate		×		×		
* Polar science support	Gov't or academia					×	
Fission waste disposal	Gov't or public utilities					×	
Climate change mitigation	Gov't	×	×		×	×	

* Early market opportunities.

11.8 SUMMARY

Clearly, an all-private approach to a Return to the Moon is not the only hypothetical approach that could be taken. The benefits of taking that approach, however, extend far beyond the human excitement and potential of being back in deep space to stay and the direct additions to the economy in doing so. The bridging and ancillary businesses related to commercial helium-3 fusion power offer near-term and very important services related to current, everyday needs and national security requirements. Helium-3 fusion power addresses critical demands for sustainable, clean energy in the twenty-first century and beyond. The reconstitution of a heavy lift booster capability, and its permanent availability at low cost, opens new doors to a better future for humankind. Most importantly, a permanent settlement on the Moon extends the benefits of human civilization and freedom indefinitely into future generations.

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12

LAW: SPACE RESOURCES

12.1 INTRODUCTION

A privately financed and managed lunar resource and helium-3 fusion power initiative, as well as any government-sponsored effort, will require a permissive if not helpful financial, managerial, regulatory, political, and treaty environment. For like initiatives to ever occur, the broad spectrum of "space law" cannot preclude such endeavors and, indeed, should encourage the private investment of human and financial resources to advance civilization's reach. A preliminary evaluation of financial and managerial approaches to a lunar resource and helium-3 fusion power initiative (Chapter 8) strongly suggests that a private approach to a Return to the Moon has significantly more chance of success than those approaches requiring major United States government or international involvement. On the other hand, the success of any approach, particularly an all-private approach, will require government's assistance in the maintenance of or, if necessary, the creation of supportive regulatory, treaty, and political environments.

The general status of the United States government's current regulatory involvement in space-related activities has no known or anticipated roadblocks to an all-private lunar resource initiative. Many regulatory hurdles exist; however, none has proven insurmountable for private entities involved in commercial endeavors related to launch, communications, remote sensing, research, and space services activities. The same conclusion can be made for current tax law, although such law certainly could be made more encouraging of all new business initiatives. Unless unforeseen adverse changes occur in regulatory and tax laws and their interpretations, an all-private lunar resource and helium-3 fusion power initiative could move forward in the context of United States' law.

The general status of international space law relative to an all-private lunar resource and helium-3 fusion power initiative appears permissive at this time, that is, no treaties to which the United States government and most other nations are party would, on their face, prevent such an initiative.[1] Indeed, the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space – 18 UST 2410 (Outer Space Treaty) – explicitly envisions "use" of celestial bodies, including the Moon, as long as that use is "for the benefit and in the interest of all countries" and is conducted "without discrimination of any kind, on a basis of equality and in accordance with international law." Political pressures, however, with regard to the interpretation of concepts included in existing treaties and proposed treaties, may become significant once such a lunar resource initiative appears to be moving toward reality.

A treaty negotiated subsequent to the Outer Space Treaty, the 1979 "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies," usually referred to as the "Moon Treaty," but more properly called the "Moon Agreement," has technically entered into force as a consequence of ratification by the minimum five nations. The absence of ratification of the Moon Agreement by the major spacefaring nations renders this treaty moot at the present time, although some would disagree with this conclusion. The appropriateness of its ultimate ratification by major spacefaring nations such as the United States will be discussed further in Section 12.4.2.

12.2 RELEVANT LAW AND PRECEDENTS

International law comprises the "law" of the present international political system that governs the coexistence of nations and includes a generally accepted body of principles, rules, institutions, procedures, and precedents. The development of international law directly or indirectly related to space is illustrated by the chronology shown in Figure 12.1. Predictable regulation of relations and interactions among nations and the non-violent resolution of disputes constitute the benefits of international law to those who recognize and adhere to it. In answer to the question, "Does it work?," most states comply with most international law most of the time.

The primary sources of international law, in order of importance, are (1) treaties or other formal agreements, binding on those nations which expressly ratify them subject to any formal reservations, (2) customary law, that is, widespread, established international practice, and (3) law common to most national legal systems. Treaties and agreements are the most important components of international law. They are legally binding only on ratifying nations, although international pressures can be applied to nations that do not ratify. Many treaties and agreements require a minimum number of ratifications to "enter into force"; however, reservations related to particular provisions may be taken by individual states as part of the ratification process.

International law specifically related to mining and processing of natural resources is complex at best. Access to state or public mineral rights can take several ownership forms. In the mining claims and leasing system followed in the United States, primarily in the Western States, for example, the miner has title to extracted minerals but not the land from which they were mined. In the Eastern United States, mineral production is commonly from private lands. In most other nations, total state ownership of minerals is assumed.

12.3 ANTARCTIC TREATY SYSTEM

The original, 1959, formulation of the Antarctic Treaty System entered into force in 1961, well before it was fully evident that treaties relative to non-defense use of space might be necessary. Nonetheless, this Treaty System became and remains a popular reference in discussions of possible

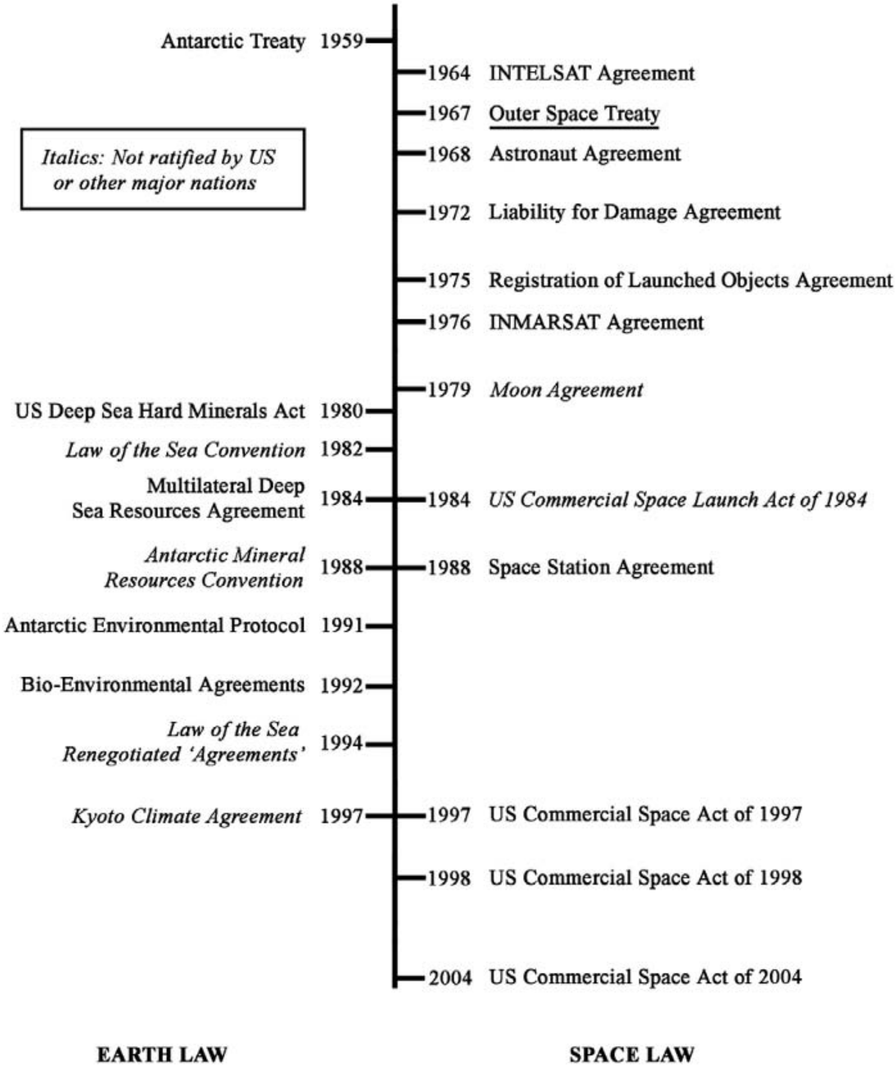

FIGURE 12.1 Chronology of International Agreements and United States Legislation directly or indirectly relevant to Space Law.

analogs for space treaties. Antarctica, like space, represents a harsh and hostile environment with no established territorial jurisdictions, although a few disputed claims to sovereignty exist. No independent human settlement exists and costly and technologically and managerially complex operations are required for exploitation of its important scientific research potential. Finally, Antarctica potentially contains abundant resources that might become economically attractive in the future.

The original 12 signatories of the Antarctic Treaty, including the major powers of the time, expressed their intent by stating, "... Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord." The originally limited framework of principles and rules has been expanded through a consultative mechanism into a distinctive legal and political regime, participated in by over 38 nations. The Antarctic Treaty System has provided a limited framework of principles and rules for the participating parties to follow. It includes mechanisms for continued consultation, unanimous approval of any changes, periodic consultative meetings, and the addition of other nations as participants.

Increased awareness of the resource potential of Antarctica led, in 1988, to the negotiation of a Convention on Mineral Resources, aimed primarily at providing a framework for decisions relative to nationally sponsored mineral exploration and extraction activity in Antarctica and on its continental shelf, while still protecting the Antarctic environment. Although not a detailed mining code, the Convention contemplated regulating resource activities, including those by private enterprise if a ratifying party sponsored such activity. Fees collected for resource activity would be used only for purposes related to the Antarctic.

Environmentalists roundly criticized the Convention as being inappropriate and inadequate.[2] Response to this criticism included passage of United States' law that made it a criminal act for United States' persons to participate in Antarctic mineral resource activity. In 1991, a Protocol on Environmental Protection superseded the Convention and designated Antarctica "as a natural reserve, devoted to peace and science" and specifically prohibited mineral resource activity. Actions required under the new Protocol include environmental impact assessments for all proposed activity in the Antarctic. It is left to nations, however, to decide which activities require such assessments. Requirements encompass protection of flora and fauna, management of waste disposal, control of marine pollution, and regulation of tourist activities. Nations who are party to the Protocol may specifically withdraw and presumably might do so when resources of sufficient value are discovered. Concern properly exists that the absence of the previous Mineral Resource Convention's regulatory regime will result in increased long-term potential for withdrawal from the Environmental Protocol and thus create more environmental stress on Antarctica rather than less.

However appropriate the Antarctic Treaty regime may be for that frozen continent, a serious mistake would be made if some of its precedents were followed closely for the Moon.[3] A prohibition on the development of lunar resources, for example, would deny humankind one of its most important options for the indefinite prolongation and betterment of civilization.

12.4 SPACE LAW

12.4.1 Outer Space Treaty of 1967

Space law has evolved along two parallel paths: one establishing general approaches and one establishing specific means of exploiting new technology, especially communications and human flight opportunities. Both paths have, to date, brought remarkable success and stability to international interactions in the space arena. As a general approach to space law, the Outer Space Treaty of 1967 builds on many of the lessons learned from the Antarctic Treaty experience, namely:

- use relatively simple, pragmatic, and flexible approaches;
- base approaches largely on the interests of the principal "user" states but leave open to all states;
- create tailored, decentralized, evolutionary institutions;
- by-pass troublesome issues of principle not requiring immediate resolution;
- recommend interim guidelines or voluntary restraints pending further experience and consultation;
- recognize that some regulation may be better than outright prohibition;
- rely on competent scientific information and advice;
- create a consultative mechanism with incentives to participate;
- pool research efforts and resources;
- provide for notice, consultation, and inspection to build confidence.

Although the conduct of space activities draws extensively on terrestrial international law and precedents, new legal issues have arisen relative to space that have required the negotiation of new treaties. One example of new issues particularly relevant to a lunar resource and helium-3 fusion power initiative is the right of access to resources from space. Does that right exist or not?

If one looks first at the terrestrial spectrum of national resource or mining law that might be drawn upon for precedents in space, one finds great diversity, particularly where the reality or perception of public ownership of land and minerals exists. National systems predominate, and the international law that exists derives from national law. Diversity ranges from open private to restrictive national ownership of land and mineral rights and, in the cases of national ownership, from mining claims or leasing systems where the miner has ownership of the extracted resources to complete state ownership of extracted resources. National mining laws offer several alternative situations for the prospective miner – the miner can own the land and mineral rights, own only the mineral rights, lease mineral rights from the owner or state, or be a contractor to the "state" owner.

State or public ownership of mineral bearing lands has its roots in ancient, sovereign rights – that is, the rights of the crown. Access to state or public mineral rights can take several ownership forms. In the mining claims and leasing system specific to public lands in the United States, the miner has title to extracted minerals but normally not to the land itself.[4] (As will be discussed further below, this actually is the regime existing under current space law.) Although the United States government regulates some environmental aspects of resource activities on private lands, it does not control the private sale or leasing of those lands or mineral rights unless antitrust issues are alleged. In much of the rest of the world, state ownership of all minerals is assumed. Minerals may be produced by the state, by state–private partnerships, or by state-managed contracts with private entities.

The implications of international diversity in national mining law include the following:

- any additional, negotiated system for access to resources from space may or may not have a role for private enterprise; and
- international governance of access may provide for any one of the following roles for private enterprise:
  - no role, that is, all resource activity will be undertaken by the international entity (see discussion of the Moon Agreement and the Law of the Sea Convention, below),
  - competitively bid concession, in return for rent and/or royalties,
  - non-competitive concession, or
  - contractor hired by the international entity.

Fortunately, in spite of this potential diversity in space mining law, the Outer Space Treaty of 1967, to which over 110 states and all spacefaring nations are parties, has been interpreted by most objective analysts as permissive relative to access to resources from the Moon. Relevant provisions and their implications relative to lunar resources include:

- "Exploration and *use* ... shall be carried out for the benefit and in the interest of all countries... and [the Moon and other celestial bodies] shall be the preserve of all Mankind." (Article I, para. 1)
  - *Implication*: Uses, such as the extraction of resources for broad-based use on Earth to raise living standards or in space to support exploration and settlement, and the environmental benefits of such use, would be, *a priori*, "for the benefit and in the interest of all countries ..."
- "The Moon ... shall be free for exploration and use by all states without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas ..." (Article I, para. 2)
  - *Implication*: Private entities, operating under license from a state, can operate anywhere on the Moon as they operate under international law throughout the world.
- "The Moon ... is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." (Article III)
  - *Implication*: This provision, along with Article I's "shall be the preserve of all Mankind" language, implies a regime equivalent to that governing the extraction of resources from the public lands of the United States, that is, a public or private entity may own the resource but the sponsoring state party cannot claim sovereignty over the land. It does not prevent, however, the establishment of a multinationally recognized regime of private property (Section 12.7).
- "Activities of non-governmental entities ... [on] the Moon ... shall require authorization and continuing supervision by the appropriate state party." (Article VI)
  - *Implication*: This wording permits private enterprise activities on the Moon provided the private entity is licensed by a state party and subject to oversight by the licensing state.

- "A State Party on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body." (Article VIII)
  - *Implication*: The civil and criminal laws of the licensing state will govern activities by a private entity on the Moon as well as events leading up to such activities.
- "States parties shall pursue studies of . . . the Moon . . . and exploration . . . so as to avoid their harmful contamination. If in doubt, consultation shall be initiated before proceeding with the activity in question." (Article XI)
  - *Implication*: This provision implies but does not mandate a need to demonstrate to other interested parties that activities by a private entity, such as the destruction of small craters, the temporary movement of dust, and the release of volatiles, will not result in detrimental effects on the activities of others. Consensus that the activity will not be harmful, however, is not required before proceeding.
- "State parties agree to inform . . . the public . . ., to the greatest extent feasible and practicable, of the nature, conduct, location and result of their activities . . . [on] the Moon." (Article XI)
  - *Implication*: This language permits certain aspects of a private entity's plans, such as the location of targeted resources, to remain proprietary at least until activities are initiated on the Moon.
- "All stations, installations, equipment and space vehicles on the Moon . . . shall be open to representatives of other states parties on the basis of reciprocity; such representatives shall give reasonable advance notice of a projected visit." (Article XII)
  - *Implication*: Once reciprocity is possible, a private entity should prepare for inspections of its facilities, however, a right of exclusivity is implied by the provision for advance notice of any inspection.

The Outer Space Treaty, on the other hand, does not contain specific rules relative to the extraction and use of lunar resources. Extraction, use, and ownership, however, are not precluded. Clearly, on the other hand, the Treaty's provisions imply certain guidelines. These guidelines, along with a private initiative's anticipated compliance, as a legal corporate entity under the laws of the United States or other state party (Article VI), are as follows:

- Binding rules of international law, including the UN Charter, govern lunar resource activities.
  - A lunar private initiative would so operate as do other entities involved in international resource extraction activities on Earth.
- Extracted resources must be used for peaceful purposes. (Articles I and III)
  - A lunar private initiative would market lunar resources within the global marketplace and not specifically or knowingly to customers with aggressive intentions for their use. Additionally, such an initiative would be governed by and restrictions on sales placed on it through its licensing state party.
- Activities related to the use of lunar resources "for the benefit and in the interest of all countries." (Article I)
  - A lunar private initiative's principal business objective would meet this guideline, namely, to provide the energy, economic and environmental benefits of lunar resources to all customers without geographic or national discrimination other than those required by law. Further, once retained earnings reach an appropriate level, the possibility will exist for shareholder approval of the endowment of a foundation for the purpose of facilitating global access to the benefits of helium-3 fusion.
- No claim of sovereignty can be made over specific territory on the Moon, nor can free access be barred to any area. (Article II)
  - A lunar private initiative would comply by operating within other provisions of the Treaty (Article XII) that implicitly recognized that it may establish stations and other installations on the Moon and require advance notice of inspections by others on the basis of reciprocity and the right of the state party (Article VIII) to exercise legal jurisdiction over such stations and their personnel.
- Contamination of the Moon is to be avoided. (Article VI)
  - A lunar private initiative would comply with this guideline. Further, it would maintain close inventory of all unused waste and unneeded hardware due to their inherent economic and potential future operational value. With respect to potential contamination due to the unavoidable release of solar wind volatiles and the activation of lunar dust during mining and extraction operations, studies by the

  astronomy community have shown that volatiles are rapidly lost to space[5] and disturbed dust migrates only very short distances due to the lack of a lunar atmosphere.

- Cooperation with, and mutual assistance of other entities operating on the Moon is required, as is advanced notification and consultation with respect to any activities which might interfere with others. (Article IX)
  - A private initiative would so comply as a condition of its license and on humanitarian grounds.
- The United States or other licensing state party, and presumably a licensed private initiative, would be liable for activities on the Moon. (Article VI)
  - A private initiative would be regulated and controlled by existing state party law and would undertake appropriate risk management initiatives as well as maintain appropriate insurance coverage.
- Openness and data exchange with other parties to the Treaty should be undertaken. (Articles XI and XII)
  - A private initiative would so comply within reasonable periods of time required for its proprietary use of data upon which its business success would depend.

The preceding analysis makes it clear that the Outer Space Treaty has a comprehensive set of provisions that currently govern resource related activities in space, including the Moon. As Joyner and Schmitt[6] summarized the literature on the Treaty up to 1984:

> The upshot of these observations suggest that certain general principles of extraterrestrial law have been established, are recognized in the practice of states, and are currently applicable to the Moon.

Further, as stated by Blider and others[7]:

> In view of the broad adherence to the Outer Space Treaty, including all states having significant space capabilities and the absence of any objection to its principles, it is persuasive that most of the provisions of the Treaty have now become part of customary international law, binding even upon states which have not ratified the Treaty, or even upon any state which might choose to withdraw.

In summary, and as an example, the following firm legal guidelines for private, resource-related operations by a properly licensed company arise from the 1967 Outer Space Treaty:

- Extraction and use of resources are not prohibited.
- Facilities and equipment belong to the company.
- An internationally sanctioned regime of private property is not prohibited.
- Permanent settlement is not prohibited.
- Civil and criminal law of the licensing country will apply.
- Binding rules of international law, as recognized by the licensing country, also apply.
- Resources must be used for peaceful purposes.
- Resources must be used "for the benefit and in the interests of all countries" as determined by the licensing authority.
- No claim of national sovereignty can be made.
- Free access cannot be denied to others provided that this can be reciprocal.
- Contamination of the Moon is to be avoided.
- Cooperation and mutual assistance to others shall be provided as feasible.
- Advanced notification and consultation relative to potential interference with others is required.
- Openness and data exchange with other parties to the Treaty is required but also, in the case of a United States' company, must be in compliance with Securities and Exchange Commission regulations.

12.4.2 Moon Agreement of 1979

Some observers point to the 1979 Moon Agreement, as effectively modifying the regime established by the Outer Space Treaty of 1967. In fact, there are many advocates for a more detailed, complex, and internationalized regime of space law than that provided by the Outer Space Treaty.[8] For example, in 1998, J. I. Gabrynowicz stated, "[T]he Moon Treaty is the agreement governing the activities of states on the moon and other celestial bodies."[9] Similarly, Declan J. O'Donnell's United Societies in Space memorandum of February 1998[10] proposes "that we re-look at the Moon Treaty because there is no other specific legal framework within which to operate." These, and similar statements, clearly are in error because the major spacefaring nations have not chosen to ratify the Agreement. Past disinterest in the consequences of ratification, however, may have disappeared in 2004 with increased articulation of plans for returning humans to the Moon on the part of the United States, China, and Japan and increased scientific interest in Europe and India.

Although the Moon Agreement in part reiterates earlier space law – particularly the Outer Space Treaty – there has been no broad-based interest in the Agreement by spacefaring nations. It technically entered into force in 1984 with formal ratification by the requisite five states plus four others. Five other nations, including France and India, have signed the Agreement but have not formally ratified it. The Agreement effectively is dormant as none of the major spacefaring nations has ratified and are thus not bound by its provisions. This lack of consensus relates to the following issues raised by Article 11 of the Agreement:

- Uncertainty over the meaning and implications of the language "the Moon and its natural resources are the common heritage of mankind" (paragraph 1). This uncertainty is particularly strong in view of the experience with the Law of the Sea Convention (see below) in which that phrase initially resulted in the near exclusion of private sector and national access to deep sea resources.
- Concern over the expansion of the Outer Space Treaty's prohibition that the Moon is not subject to national appropriation by any claim of sovereignty to include "by means of use or occupation, or by any other means" (paragraph 2).
- Concern over the strong prohibition on ownership of "natural resources in place ... surface or the subsurface of the Moon ..." (paragraph 3), which, although consistent with the Outer Space Treaty's less explicit provisions, raises questions about the ownership of extracted resources when taken in conjunction with paragraph 5's apparent prohibition of non-international "exploitation of natural resources."
- Statement that "Resources may be used to support activities on the Moon" (Article 6, paragraph 2) might be interpreted as a restriction on the use of resources for broader purposes although it appears that this was not the intent.
- Prevention of the disruption of the existing environment balance (Article 7) with detailed obligations left open.
- Change from "reciprocal" access must be accommodated, as stated in the Outer Space Treaty, to a statement that free access of other parties cannot be impeded (Article 9) potentially would seriously encumber resource production activities even if ultimately allowed under a renegotiated Agreement.
- Undefined nature or even the desirability of the "international regime...to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible" (paragraph 5). Any disagreeing state will not be legally bound by the negotiated management regime, however, private investors will be concerned about the resulting political discord and potential uncertainty.

- The quantitative meaning of the purposes of the international regime stated in paragraph 5, particularly, "an equitable sharing of all States Parties in the benefits derived from [the natural] resources [of the Moon] ..." (paragraph 7d)

Other sections of the Agreement also raise concerns, including those in Article 16 that imply an one nation-one vote structure for the international organization envisioned in Article 11, paragraph 5, and those in Article 18 related to the convening of a "review conference." Article 18, when taken with Article 11, builds in a high degree of uncertainty that is antithetical to private commercial as well as independent national activities on the Moon. In effect, these two Articles would create a moratorium on such activities until the review conference and new provisions to the Agreement are ratified. Further, Article 11 mandates an international regime that would both complicate private commercial efforts and give other countries political control over the permissibility, timing and management of all commercial activities.

Eilene Galloway points out (personal communication)[11] that in response to concerns about a potential moratorium, S. Neil Hosenball, then General Counsel of NASA, stated:

> There is no moratorium in the Treaty on the exploitation of natural resources either pre-regime or if a state chooses not to become a party to the Treaty establishing such a regime. Proposals for such a moratorium were submitted for the record by India, Italy and other delegations. No such provisions appear anywhere in the Treaty and the United States through numerous statements in the record said it would not accept a moratorium.

As discussed above, however, Articles 11 and 18, taken together, would create a *de facto* moratorium in spite of no mention of a specific moratorium in the body of the Agreement.

Debate during Senate Commerce Committee hearings in 1980, in which I participated as Chairman of the Subcommittee on Science, Technology, and Space, not only focused on the above concerns, but on potential interpretations of language in Article 11 providing that "... the Moon and its natural resources are the common heritage of mankind." Although Article 11, paragraph 1, states that the "common heritage" concept "finds its expression in this Agreement," concern remained that future negotiations and interpretations would follow the more detailed formulation of the Law of the Sea Convention being considered in the same time frame. At the time, this Convention provided that "common heritage" resources could only be developed under the aegis and supervision of an international organization with a one nation–one vote, majority rules, structure. This history, taken together with the Moon Agreement's mandated international regime (Article 11, paragraph 5), and opposition by various United States Presidents since, has prevented further Senate consideration of the Agreement.

12.4.3 Intelsat and Inmarsat

As I have suggested elsewhere,[12] the private sector might be able to interact effectively with a *user-based* international regime, modeled after the successful Intelsat and Inmarsat agreements, if that were to be the outcome the Moon Agreement's Article 18 conference. Contrary to some suggestions,[13] lunar energy resources are so vast and the mutual international interest in long-term energy supplies so strong that significant similarity can be seen relative to telecommunications resources, the basis for forming those two organizations. A user-based regime like the original Intelsat certainly would be demonstrably more workable than a one nation–one vote regime (see Chapter 8). In view, however, of the international, one nation–one vote atmosphere surrounding both the Law of the Sea Convention and the Kyoto conference on global climate change, such an outcome from a Moon Agreement conference appears unlikely. Further, in spite of their early decades of success, the Intelsat and Inmarsat organizations now are moving rapidly toward privatization. The window of opportunity for following this particular international course with respect to the use of lunar resources appears to have closed.

12.5 LAW OF THE SEA CONVENTION

The Law of the Sea Convention of 1982 (provisions were well known by 1980) contained many potentially harmful precedents relative to any future additions to current space law. Its negotiation was prompted by the discovery, in 1950, of large areas of deep seabed manganese–copper–nickel–cobalt nodules as well as phosphate deposits. There were many, long-festering freedom of the seas, environmental and other issues also needing to be addressed. The United Nations and most developing countries wanted an international framework governing access to seabed resources that would ensure that the United States and other developed nations would not be the sole beneficiaries of these resources. Little interest in such a convention existed in United States' political circles in the early 1980s as the proposed convention clearly would deter resource development. The Convention would create a lack of certainty in granting licenses to access resources, artificial limitations on production, financial burdens of fees and taxes, mandated transfers of technology, and inadequate participation for the United States in the decision-making and amending process. Further, any fees generated could go to so-called national liberation movements.

Then, in 1980, the United States created the "Deep Seabed Hard Minerals Act" that authorized the National Oceanic and Atmospheric Administration (NOAA) to license United States nationals for deep seabed mining. In 1983, President Ronald Reagan, by executive order, created the "Exclusive Economic Zone" (EEZ) that extended national authority to 200 miles offshore. Also, in 1984, a multilateral agreement between the United States, United Kingdom, France, Belgium, Germany, the Netherlands, and Japan provided for these nations to respect each other's licensing decisions relative to seabed mining.

In spite of United States' concerns and actions, 135 nations, including the European Common Market, originally signed the Law of the Sea Convention with 65 ratifications by September 1994, meeting the 60 ratifications necessary for the Convention to enter into force. Fifteen important nations, however, did not sign, including the United States, the then Soviet Union, the United Kingdom, the Netherlands, Italy, and Japan. In this situation, it became clear that the Convention could not live up to even its advocates' expectations. The Convention subsequently was renegotiated and resubmitted to the United States Senate for ratification by President Bill Clinton in 1994 (Treaty Document 103–39). Although 100 nations now have ratified this renegotiated Convention, as of December 2004 no action is pending in the Senate. The current Chairman of the Foreign Relations Committee, Richard Lugar, however, has indicated that he now supports ratification on the basis of the "damage to US interests that could occur if we choose not to ratify it."[14]

Although the renegotiated Convention improves the environment for most private sector activity related to the seas (regulated by the United States but apparently independent of any established international authority), the meaning of the "common heritage" concept, as it pertains specifically to mining, remains much as in the original Convention, that is, such activity is subject to approval and regulation by the Convention's International Seabed Authority and subject to competition from that authority through its own "Enterprise." This is contrary to the assertion of William M. Daley, Secretary of Commerce in 1998, that the new treaty "reformed the deep seabed mining provisions along free-market principles."[15] Modifications do not necessarily mean reform. Also, the Convention contains a compulsory dispute settlement provision that would specifically negate United States' sovereignty, a problem with many currently pending international agreements. Thus, the potential precedents of the Law of the Sea Convention, should it be ratified by the United States, continue to pose interpretive difficulties for possible private commercial activity related to lunar resources under a ratified Moon Agreement.

12.6 UNITED STATES' SPACE LAW

A wide variety of United States' law and regulatory interpretations of law already govern the activities of private and government entities that go into space. These include, but are not limited to, the following:

- The Communications Act of 1934 and amendments and regulations promulgated thereto that provide for radio frequencies allocation and limits on use of those frequencies.
- The Environmental Protection Act of 1970 and amendments and regulations promulgated thereto that will govern all corporate and national activities, particularly manufacturing and rocket launches.
- Commercial Space Launch Act of 1984 and amendments and regulations promulgated thereto that provide for the regulation of space launch activities.
- Commercial Space Acts of 1997 and 1998 and amendments and regulations promulgated thereto that provide for launch licenses, return payload licenses, and protection of space assets as private property.
- Commercial Space Launch Amendments Act of 2004 that focuses particularly on human space flight and provides further licensing control over private space activities, the indemnification of private launches, and a framework for space tourism.

Legislative and regulatory activities that directly or indirectly would affect a Return to the Moon obviously would require careful scrutiny by any entity intent on accessing lunar resources.

12.7 PROPERTY AND MINERAL RIGHTS

Much has been written for and against the development of a regime of private property rights for the Moon and other celestial bodies. Such rights would significantly increase incentives for private investment in a Return to the Moon although they may not be absolutely required for eventual success. Clearly, once a permanent settlement in space declares political and corporate independence from Earth, this issue becomes moot and any private property regime will be determined by residents of the settlement, as has often been the case throughout history. Until then, the Outer Space Treaty's recognition that objects placed in space (including those of private companies) are owned by their sponsoring entity plus international acceptance of the United States' extension of property rights to products sent to or produced in space (Commercial Space Act of 1998) are important precedents in this regard.

The Outer Space Treaty's prohibition on assertions of national sovereignty over bodies in space has been taken by some to preclude the establishment of property rights over land on the Moon or elsewhere in space. Indeed, officials from many developing countries and many other individuals have argued for the establishment of an international regime to govern access to lunar resources with the effective designation of the Moon as an international "commons."[16] This has been their interpretation, certainly a correct one, of the "common heritage" language of the Moon Agreement and, indeed, this clearly is the specific intent of the Agreement.

The legal, political, and economic difficulties in defining and managing a common resource are extensive and well documented in human history.[17] What has been termed "the tragedy of the commons" is well documented in both the abuse and the lack of productivity that comes with a "commons" designation.[18] Left out of most arguments both for and against a commons approach to managing access to lunar resources, however, are the benefits that come to all from a successful harnessing of lunar helium-3 fusion,[19] focusing instead on the direct financial returns that might accrue to those who take the development risks. The Earth's environment, overall standard of living, and political interactions over terrestrial energy sources will all improve with the availability of this new source of global energy.

In this context, the opportunities and benefits of private enterprise in developing lunar resources would disappear if the United States should ratify the Moon Agreement.[20] If international political interference with a Return to the Moon is to be avoided, the United States and other spacefaring nations should unequivocally reject this Agreement even though they helped to negotiate it. This would remove any residual uncertainty that its provisions might be agreed to at some time in the future. As lunar resources are important to the future of humankind, both in space and on Earth, entrepreneurs in the United States and elsewhere will need to see to it that the so-called Agreement disappears from further consideration.

In removing the Moon Agreement from the playing field, the United States and other nations could state that their policy will be to license competent entities to bring lunar resources to Earth under the general authority and constraints of the Outer Space Treaty of 1967. More proactively, these nations could state in policy and law that, under specific conditions, they will recognize a private entity, or other entity's property and mineral rights within a requested area on the Moon. The conditions for granting recognition of property and mineral rights could be as follows:

- The requested area is no greater than about 3.3 degrees longitude and 3.3 degrees latitude at the lunar equator, or about 10,000 km^2 , these dimensions increasing with each 10 degrees of latitude to maintain an approximately constant area.
- The property and mineral rights in the requested area have not been recognized previously on behalf of a prior requestor.
- The requestor has received, or receives prior to occupation of the requested area, all applicable licenses from the United States or another cooperating state.
- The requestor has not been granted a similar request in the last five years.
- The requestor has provided independently audited financial statements and management controls documentation, updated each year, that show that financial commitments and managerial capabilities exist that are adequate to initiate production of resources and/or provide services from within the requested area within 20 years of the granting of the request.
- The requested area does not include, or specifically protects, important scientific or historical sites and has been approved in this regard, relative to United States licensed entities, by the National Academy of Sciences and Smithsonian Institution.
- Granted property and mineral rights may be sold or traded, separately or together, in part or in whole; however, new owners must meet and continue to meet the original conditions of the grant of rights.
- Granted rights may be renewed indefinitely for 20-year periods as long as production and services continue and the original conditions of the grant continue to be met.
- Granted rights may be transferred permanently, in whole or in part, to the residents of any permanent lunar settlement on the granted parcel after the first 20-year grant period has been completed.

- Grantees, or their assigns, will commit to adhere to applicable provisions of the Outer Space Treaty of 1967.
- The requestor agrees that legal jurisdiction over its activities, and those of its assigns, will reside in the licensing state until jurisdiction is established by a permanent settlement on its granted parcel.
- Granted rights may be revoked if any of the following conditions are met by the grantee or its assigns:
  - Production of resources or provision of services has not begun within 20 years of the grant.
  - Willful failure to adhere to applicable provisions of the Outer Space Treaty of 1967.
  - Three contiguous years of qualified opinions from the grantee's independent auditors, or those of its assigns, that the grantee lacks the ability to meet the conditions of the grant.
  - Discrimination in the sale of the grantee's resources or services, or those of its assigns, except for cause, such as, a state of war existing between the grantee's licensing state and that of the customer, non-competitive financial considerations, or legal restrictions imposed by its licensing state.
- The United States and cooperating states may grant waivers to the above revocation conditions in special circumstances, with disputes relative to such waivers considered under standard arbitration procedures. Arbitration decisions may be appealed through the court system of the licensing state.
- Notwithstanding other provisions of law, grantees and their assigns, licensed by the United States or a cooperating nation, will be liable solely for actual damages, as determined by a court of appropriate jurisdiction, in the event of accidents related to activities pursued in exercise of their granted rights. Consideration might be given to establishing a "political risk insurance pool" to deal with risks outside the normal course of business.[21]

This multilateral approach to the establishment of a regime of property and mineral rights for the Moon represents an investment based "auction." Such an approach, in contrast to a monetary auction, as suggested by some,[22] would accelerate the availability of the benefits of lunar resources and services by putting potential auction payments to work as investments toward achieving that goal. It also would be consistent with a regime of "first possession" suggested by Glenn Reynolds[23] and would be a means of implementing and systematizing such a regime. The 1984, multilateral agreement between the United States, United Kingdom, France, Belgium, Germany, the Netherlands and Japan relative to licensing access to deep sea resources constitutes a potential precedent for this approach to recognizing property and mineral rights in space.

12.8 CONCLUSION

The only space treaty directly related to the use of resources from space to which the United States and other spacefaring nations are party, the 1967 Outer Space Treaty, specifically provides a generally recognized legal framework for such use. The Outer Space Treaty does not contain specific rules relative to the extraction and use of lunar resources. The Treaty's provisions, however, imply certain guidelines that should be adhered to by any national or private effort to use lunar resources. Compliance with the Treaty's guidelines by a legal corporate entity under the laws of the United States or other state party would be straightforward, provided the state party chooses to be enabling rather that inhibiting.

The Moon Agreement, if ratified by major spacefaring nations, would create a high degree of uncertainty that is antithetical to private commercial activities on the Moon. The Agreement would, in effect, create a *de facto* moratorium on such activities. A mandated international management regime would both complicate national and private commercial efforts and give other countries political control over the permissibility, timing and management of all commercial and national resource activities on the Moon.

Finally, the question can be asked, "Absent an international management or regulatory authority, what guarantees are there that a properly licensed private entity will comply with the Outer Space Treaty's provisions and guidelines?" First of all, the licensing state can withdraw its launch, communications, and return licenses for cause and enforce compliance before they are re-activated. If the licensing state does not act to force compliance, the world community can bring the matter to the World Court and/or join in part or in whole to enforce sanctions against the offending entity and licensing state. Any one of these actions would have a serious impact on the private entity's ability to maintain its space operations, other than those related to safety of personnel, or its access to the capital and customer markets upon which its ability to do business would depend.

Chapter 12

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HUMANS: ROLES IN SPACE

13.1 INTRODUCTION

TRADITIONALLY, "Space exploration" has implied both human and robotic exploration of the Moon, planets, and asteroids – that is, exploration of deep space. This is in contrast to other space activities that take advantage of both the weightless environment found in Earth orbit and the special benefits of observing the Earth and stars from that vantage point. Human activities in Earth orbit now have less to do with exploration and more to do with international responsibilities and commitments, as in the case of the International Space Station, and prestige and technological development, as in the case of certain efforts by the United States, Europe, China, India, and Russia. Unique and unexploited research opportunities, however, still exist in near-Earth space, but these have not been fully recognized even after half a century of repetitive access. For example, research initiatives in biomedicine and weightless manufacturing have yet to be undertaken in comprehensive ways.

Deep space exploration should always be conducted by employing the best combination of human and robotic techniques. In this context, many will argue the value of robotics. Indeed, any data collection that can be successfully automated at reasonable cost should be. In general, human beings should not waste their time with activities such as surveying, systematic photography, and routine data collection. Robotic precursors into situations of undefined or uncertain risk to humans are also clearly appropriate.

Direct human exploration, however, offers exceptional benefits that robotic exploration currently cannot and probably will not duplicate in the foreseeable future, certainly not at competitive costs (Figure 13.1). What is pertinent here is the value of field geology and field biology, for example, conducted by trained and experienced natural scientists or challenging space-piloting tasks undertaken by trained and experienced test pilots. Some of my scientific colleagues have made the argument that everything we learned scientifically from Apollo exploration could have been done robotically. Not only do the facts *not* support this claim, but also such individuals have never been required to present a detailed accounting of the cost of their alternative robotic exploration program. Robotic duplication of the vast scientific return of human exploration of six sites on the Moon[1] would cost far more that the approximately $11 billion spent on science (author's estimates in today's dollars) and probably more than the estimated $140 billion total cost of Apollo ($22 billion in 1966 dollars).

What do humans bring to the exploration table (Figure 13.2)? First, there is the human brain – a semi-quantitative super computer with the foundation of hundreds of millions of years of Nature's "research and development" and several million years of accelerated refinement based on the requirements for survival of primates. The brain is both programmable and instantly re-programmable on the basis of training, experience, and immediately preceding observations.

Second, there are the human eyes – a high resolution, stereo optical system of extraordinary dynamic range that are also the consequence of nearly four billion years of trial and error with various and gradually more complex electromagnetic sensing cells and organs. Integrated with the human brain, this optical system continuously adjusts to the changing visual and intellectual environment encountered during exploration of new situations. In that sense, field geological and biological exploration is little different from many other types of scientific research where

FIGURE 13.1 The author using the Apollo A7LB pressure suit (spacesuit) and backpack while sampling regolith in the Valley of Taurus–Littrow, December 14, 1972. (NASA Photograph AS17 134 20425)

FIGURE 13.2 The author beginning the examination of a large boulder near the base of the north wall of the Valley of Taurus–Littrow on the Moon, December 16, 1972. (NASA Photograph AS17 140 21497)

integration of the eyes and brain are essential parts of successful enquiries into the workings of Nature.

Third, there are the human hands – a highly dexterous and sensitive biomechanical system, also integrated with the human brain as well as the human eyes, and also particularly benefiting from several tens of million years of recent development. We so far have grossly underutilized human hands during space exploration. The potential exists to bring the hands fully to bear on future activities possibly through integration with robotic extensions, incorporation of micro-mechanical devices into gloves, or development of physiologically compatible, skin-adhering pressure gloves.

Fourth, there are human emotions – the spontaneous reaction to the exploration environment that brings creativity instantly to bear on any new circumstance, opportunity, or problem. Human emotions also are the basis for public interest and support of space exploration, interest beyond that which can be engendered by robots. Human emotions further create the very special bond that space exploration has with young people, both those of all ages in school and those who wish to participate directly in such adventures.

Discovery of the critically important orange pyroclasitc glass during Apollo 17's study of the valley of Taurus–Littrow illustrates the unique capabilities of humans as well as any experience in the history of exploration.[2] And, if any experienced human field geologists had been exploring in place of the recent pair of Mars Exploration Rovers, they would have quickly resolved most doubts about the nature of the various outcrops. They also would have explored far more terrain, rapidly integrating their findings into the big picture of Martian history. Human explorers would have been able to test the hypotheses that *Opportunity* was exploring outcrops of sulfate-rich evaporites or the oxidized remains of the Martian equivalent of an epithermal (relatively low temperature) sulfide deposit, confirming or rejecting either idea in favor of a better one based on close and highly flexible observation and on the judicious use of a geological hammer.

Additionally, there is the natural, primordial urge of the human species to expand its accessible habitats and thus enhance the probability of its long-term survival. Deep space exploration by humans provides the foundations for long-term survival through the settlement of the Moon and Mars in this century, and the Galaxy in the next.

Finally, there is a special benefit that flows from deep space exploration by Americans and their political partners – the continual transplantation of the institutions of freedom to human settlements in space. This is our special gift and our special obligation to the future.

13.2 ADAPTATION TO SPACE

To the everlasting credit of NASA's early managers, aerospace medical team, and the courageous first astronauts and cosmonauts, human space flight began in the early 1960s with an intuitive confidence that physiologically and psychologically all would go well with our first ventures into that "new ocean." Long-term success of a lunar settlement, however, will require more than intuition. That success will be signaled to history by permanent exposure of humans to the lunar environment. More critically, history will need to record the growth of families on the Moon as much as record a settlement's ability to support itself through use of lunar resources and the trading of those resources with customers elsewhere in space. In fact, full human adaptation to the total lunar environment – physical, psychological and cultural – in large measure will determine whether a true permanent settlement is possible or whether a continuous rotation of production and service personnel will be the norm.

Humans have had almost half a century to learn about their ability to physiologically adjust to or compensate for the adverse effects of extended exposure to the near-Earth space environment. A great deal of anecdotal, qualitative and narrowly focused quantitative information exists on individual responses to being in space. In spite of this database, neither NASA nor the former Soviet Union, now Russia, have produced a comprehensive, scientifically credible understanding of space physiology. The most important fact, nonetheless, is clear: humans can be very productive in the space environment for periods of over one year and can slowly re-adapt to the Earth's environment on their return. It also is clear that we know very little about the basic mechanisms of space adaptation or about the best and safest means of countering its various challenges.

Our knowledge of human adaptation in the significantly different environment on the Moon is even more limited. We know, of course, that humans can also be very productive working on the lunar surface, at least for several times the three days maximum of Apollo. We have direct and indirect data on many human factors related to specific use of the Apollo 7LB pressure suit, such as, metabolic rates, heat loads, mobility, and the like. We lack, however, the kind of basic physiological data on a sufficiency large number of individuals that would be necessary to provide lunar employees and settlers with long-term access to occupational medicine and general health care. Although the Apollo experience gives us confidence to proceed with lunar operations that will lead to permanent settlement, the gathering and scientific analysis of more detailed information will be an important adjunct to the first few years of a Return to the Moon.

In recent years, NASA has gradually broadened its research priorities, particularly in the SpaceLab missions of the Space Shuttle, to include emphasis on the systemic problems of space adaptation rather than just concentrating on the more obvious symptoms of space motion sickness.[3] The Agency, however, has continued to resist any true partnership with the National Institutes of Health (NIH). As mentioned previously (Section 10.7), the leadership of the NIH and I formulated a proposal for such a partnership in 1986. Our hope was that NASA would provide the in-space research opportunities and the NIH would conduct the peer review in the context of a jointly developed, overall research integration plan. When presented with the proposal, the then NASA Administrator's reaction was, "I don't want those people in my knickers!" Not much has changed since then.

The potential value of a true partnership between NASA and the NIH is much greater today than it was even in the 1980s. NASA and its international partners have built, and are planning to expand, a world-class biomedical research facility called the International Space Station (ISS).

Now, the President has directed NASA to prepare for long-duration flights to Mars and long-duration stays on the Moon. The NIH continues to be a world-class biomedical research agency with a world-recognized peer review system. As naïve as it sounds, the time is ripe for putting bureaucratic competition aside and beginning to do the job properly for a change.

13.2.1 Physiological adaptation

The primary differences in the physiological environments in a spacecraft in Earth orbit[4] and that to which we are exposed at the Earth's surface are as follows:

1. Weightlessness (freefall) instead of Earth's gravity (free fall in Earth's gravity is balanced by orbital velocity giving a condition of continuous free fall).
2. Excess oxygen atmosphere – 5-psi atmosphere with a starting 80/20 nitrogen/oxygen atmospheric ratio gradually bleeding to 0/100 (Apollo) or 15 psi with a 60/40 nitrogen/oxygen atmosphere (Skylab, Space Shuttle, International Space Station). This compares with 14.7 psi, 80/20 nitrogen/oxygen atmosphere at the Earth's surface. Partial pressure of oxygen is then about 3 psi at sea level.
3. Continuous, high-level noise (International Space Station) relative to most terrestrial work conditions.
4. Ninety-minute diurnal cycle in low Earth orbit (masked for sleep periods).
5. Cosmic and solar particle radiation intensities far greater than at the Earth's surface (annual dose of about 7 rem[5] vs about 0.36 rem, respectively).[6] Recent dosimetry for Space Station astronauts indicate exposures at least quadruple those allowed for terrestrial workers operating in the vicinity of radiation sources.[7]
5. Absence of Schumann electromagnetic resonance (lightning-induced resonance between the ionosphere and the Earth's surface,[8] broadly at 7.8 Hz, the same low frequencies as brain waves).

On the Moon, the primary environmental differences from Earth orbit have been as follows:

1. One-sixth of Earth's gravity.
2. Continuous 3.7-psi pure oxygen atmosphere in habitats and spacesuits (proven acceptable by Apollo for at lease some factor over three days).
3. Cosmic and solar particle fluxes are variable but will give an unprotected annual dose of about 25 rem vs about 7 rem at the International Space Station and 0.36 rem on Earth.[9]

4. Twenty-eight Earth-day diurnal cycle.
5. Fine mineral, rock, and glass dust (about 50% of regolith is composed of less than 50-μm particles).

The assumption of a 3.7-psi pure oxygen atmosphere for lunar habitats and spacesuits, or even one at 3.0 psi, appears to be justified by the Apollo flight experience. No adverse side effects of doing so are known and the operational benefits are several:

1. Cost and complexity of designing, manufacturing, managing, and maintaining a one-gas system will be significantly less than that for two gases.
2. Cost, complexity, inefficiency, and risk are eliminated in the preparation for extravehiclular activity (EVA), and prebreathing pure oxygen to prevent the bends (nitrogen necrosis) becomes unnecessary.
3. Mobility in pressure suits will be increased over the current 8.0-psi suits used by NASA.
4. Sea level partial pressure of oxygen presents no increase in physiological or fire risk.
5. If atmospheric nitrogen is required for the synthesis of nitric oxide in the lungs,[10] research can determine the frequency of exposure to nitrogen that is necessary to maintain required levels.

Understanding of the systemic, physiological basis for space adaptation in response to the above conditions remains incomplete. The lack of an adequate physiological baseline currently inhibits our ability to provide well-considered plans for preventive and occupational medical care of lunar settlers. What we do know about adaptation to the Earth-orbit space environment,[11] however, helps both in considering the role of humans in a Return to the Moon and in the development of a scientifically credible approach to preparing for their well-being and medical care.

There are deeply seated reasons why our understanding of space physiology and adaptation remains so limited. The first Administrator of NASA, T. Kieth Glennan, clearly recognized that adaptation issues would be important in human space flight. By his own admission, however, he failed in attempts to organize and properly manage research in this field either within NASA or as a NASA partnership with the National Institutes of Health (NIH).[12] The Mercury and Gemini flight experiences provided only very few hints that adaptation to space flight would be a significant future issue. Due to lack of space, crews were unable to move out of their couches during these flights, except for the highly intense extravehicular activity (EVA) periods, and generally did not report any adaptation symptoms. The wide use of aspirin, frequency of urination, and photographs of puffy faces indicated, however, that adaptation was underway.[13] Also, the shortness of most Mercury and Gemini missions and the load of planned and unplanned activities (rendezvous demonstrations, EVAs, unexpected emergencies, etc.) would mask the effects of multi-sensory conflict as mental concentration was focused on completing each task (sympathetic nervous response). This masking effect occurs commonly during human exposure to unusual air and sea motions; generally, pilots and sea captains have no symptoms of motion sickness while many, more passive passengers do (parasympathetic nervous response).

After the Mercury and Gemini flights made it clear that humans could function and function well in space, operational concern about space adaptation understandably decreased. With the advent of larger volumes in the Apollo spacecraft, however, and the relatively unconstrained movement it allowed, some astronauts admitted to or showed indications of short-term symptoms of motion sickness associated with moving around in weightlessness after launch (nausea, headaches, loss of appetite, dehydration, etc.). These largely temporary symptoms clearly resulted from multi-sensory conflict between the vestibular (inner ear), visual, and muscular systems of the body. These reports and related indicators initiated within NASA an increased emphasis on research related to the gravity-dependent sensors of the inner ear, and requests for proposals from the scientific community. In fact, adaptation to space became known as "space motion sickness," a term still broadly used by NASA today. The possibility that there might have been a systemic physiological response to this new environment was de-emphasized in spite of many indications that space adaptation involved broad physiological reactions to the space environment, including changes such as fluid loss, red cell loss, muscle atrophy, and bone density reduction.

I know from personal efforts to influence these matters that NASA research priorities focused largely on the vestibular system for many years. The internal and external researchers in this field became embedded in the planning and peer review structure of NASA's space biomedical initiatives, and broader viewpoints were largely excluded. Investigations and their Principal Investigators were approved in narrow research specialties without the benefit of an overall research protocol that ultimately could tie all the individual efforts together and fill in any investigative gaps that appeared.

This situation persisted through the 1980s even in the face of the results of the relatively well-conceived and conducted Skylab investigations[14] on longer-term adaptive effects. The three Skylab missions in 1975–1976 none the less began to disclose that more was happening physiologically than just multi-sensory conflict involving the vestibular organs.[15] Skylab crews were exposed, respectively, to 28, 59, and 84 days in Earth orbit. Their initial physiological state had been well characterized prior to launch, daily monitoring of changes to that state occurred during flight, and the process of re-adaptation was also closely documented.

These Skylab flights, and limited empirical and anecdotal evidence from other missions, showed that "space motion sickness" symptoms disappeared after a few days in all but about 2% of individuals, and fluid and red cell loss stabilized at levels about 10% lower than Earth surface values. Symptoms of other long-term, systemic changes to the body also became apparent, of which only hints had been observed during some Apollo flights. For example, Skylab investigations showed that muscle, including heart muscle, continued to atrophy and bone density continued to decrease in most individuals in spite of the daily exercise program. Evidence of significant changes in overall body and blood chemistry also came from the Skylab analytical studies. Subsequently, it has been noted that the immune system increases its production of neutrophils (85% increase) and white cells in general (>50% increase) before, during, and post-flight, probably due to overall stress.[16] These conclusions emphasized the systemic, physiological nature of the space adaptation process, but failed to significantly change NASA's approach to space biomedical investigations. Indeed, as stated earlier, NASA still continues to use the term "space motion sickness" to refer to the overall symptoms of adaptation rather than the more generic term of "space adaptation syndrome." Additionally, test subjects have been astronauts and cosmonauts, most of whom have a built-in conflict of interest as test subjects – that is, they all would like to fly in space again. This may have, and probably has, colored some of their descriptions of adaptation symptoms.

Observations during Space Shuttle flights, particularly those that included the SpaceLab module, confirmed the Apollo/Skylab observations and began to suggest some limited countermeasures against their adverse consequences.[17] The experience of the former Soviet Union and subsequent Russian missions indicated that cosmonauts had had similar reactions as the American astronauts to the space environment. The cosmonauts' extended duration flights confirmed that the longer the exposure to space, the longer the re-adaptation required. In the 1990s, NASA began to expand its research efforts to include more of the long-term effects; however, a truly credible scientific research protocol has yet to be developed.[18]

Each individual adapts differently and at different rates during exposure to the environment of near-Earth space flight.[19] This reflects both different physiologies and different levels of concentrated mental activity during early phases of a specific mission. By analogy, there will also be differences in individual adaptation to the lunar surface environment. Of the major identified symptoms of adaptation to the Earth-orbit environment, Table 13.1 gives the approximate percentage of astronauts who experienced those symptoms based on my personal observations and on other reports. Because of NASA's restriction of independent access to the biomedical data on specific astronauts, based on an inappropriate use of "privacy" restrictions, a full independent analysis of flight experience and changes in individual responses from flight-to-flight has not yet been possible.

TABLE 13.1 Summary of adaptive responses by astronauts to exposure to space flight in Earth-orbit

Symptoms	Percent
Short-term (3–4 days)	
Fluid shift to upper body	100
Increased urination	100
Decreased appetite	Common
Headache (including increased aspirin use)	Common
Motion-related nausea	67–73[20]
Projectile emesis	~11
Mid- to long-term	
Motion-related nausea	~2
Red cell mass decrease (stable at 90% of pre-mission values in 2 months)	100[21]
Blood volume decrease	100[22]
Bone atrophy/density loss (average 2.2–2.7%/month)	100[23]
Muscle atrophy	100[24]
Orthostatic intolerance	100[25]
Physical work capacity decrease	100[17]
Nitrogen balance negative	~100[26]
Heart size decrease (even with exercise)	~100[27]
Cardiovascular changes	~100[28]
Cellular responses	100[29]
Blood chemistry changes	~100[30]
Fluid and electrolytes	–
Renal hemodynamics[31]	–
Endocrine secretion	–
Immune system activation[32]	–
Circadian rhythm altered	~100[33]

Clearly, adaptation to flight in Earth orbit constitutes a systemic response of most, if not all, major physiological systems to the change from normal terrestrial conditions. Weightlessness probably represents the principal change, but other differences outlined earlier may also play a significant role. As part of the process of adaptation, short-term responses must be understood. Short-term responses, in and of themselves, will not be an issue for lunar settlers, particularly if an individual's susceptibility to prolonged exposure is determined prior to selection as a potential settler. It also may turn out that a small amount of gravity, that is, the one-sixth gravity of the Moon, is sufficient to stimulate most, if not all, re-adaptation responses.

Unfortunately, over 40 years of space experience has not included a scientifically credible research protocol that integrates investigations of the body's systemic responses as well as specific components of those responses. As discussed above, the blame for this lies with the management of space biomedical research programs and the unwillingness of NASA to join with the National Institutes of Health (NIH), the Food and Drug Administration (FDA), and the broad academic research community in the development of an appropriate research strategy backed up by a world-class peer review system.

Ultimately, investigation of space adaptation to the environments of Earth orbit and the lunar surface must be fully undertaken either by NASA with the NIH, FDA, and academia or by the private sector and the NIH, FDA, and academia. Any private initiative to Return to the Moon must include the cost and timing of this research in its planning, although it is an obvious area in which government should be a cooperative research partner. A scientifically credible protocol for the study of human and animal responses to the space environment requires the following elements:

1. Research plan and investigator selection (NIH led but coordinated with private initiative and the International Space Station operational management).
2. Peer-review of proposals and final implementation plan (NIH led).
3. Selection of non-astronaut physician research team (NIH led in coordination with ISS operational management and the private initiative).
4. Operational acceptability of implementation plan (coordination between NIH, the private initiative, and ISS operational management).
5. Implementation (NIH and the private initiative in coordination with ISS operational management).
6. Analysis and synthesis (NIH and private initiative).

7. Iterate research plan and above steps 2–6 based on findings (jointly by NIH and private initiative).
8. Countermeasures protocol development (jointly by NIH, FDA, and the private initiative coordinated with ISS operational management).
9. Repeat steps 1–6 above for countermeasures protocol development.

One of the most important aspects of the above approach to space biomedical research lies in the selection of non-astronaut clinical research physicians and physiologists to conduct the space-based research protocols. To avoid conflicts of interest, these individuals' careers should depend on what they learn and how it is analyzed rather than on how often they fly in space. These space researchers should be fully integrated into the research teams and their planning and implementation process. They should fly in pairs in order to observe each other, and should do so repeatedly. Each pair's first task would be to document fully the short-term and mid-term space adaptation symptoms seen and measured for each other, and then to examine each other's response to various controlled situations that challenge physiological responses. On a subsequent flight and after analysis of data related to each pair, a standard countermeasures protocol, including investigation of the effect of one-sixth Earth's gravity if feasible, should be tested on each pair. Gradually, this approach would build much of the desired database for permanent settlement of the Moon as well as for long-duration flights to Mars.

Given what is now known, the first line of defense against the adverse effects of adaptation to one-sixth of the Earth's gravity will be gravity itself. It is not known whether strenuous activity in one-sixth gravity provides sufficient stress to prevent long-term bone demineralization, muscle atrophy, and various other physiological changes, although the personal rapid re-adaptation of my 11 colleagues and I after landing on the Moon suggests that one-sixth gravity has a disproportionally large effect. Determining the effects of one-sixth gravity will be a primary component of a future space biomedical research program, probably including exposure of research animals at the International Space Station to lifetime centrifuge acceleration that simulates one-sixth gravity.

The second line of physiological defense will be exercise. All settlers will be required to complete a daily exercise protocol designed to provide skeletal, muscular, and other physiological stresses necessary to maintain near-terrestrial standards. It is not clear that appropriate exercise protocols have been devised that can maximize this defense against space adaptation.[34] Weekly physical examinations also will be required that will include measurements of bone density, muscular strength, cardiovascular performance, and physiological chemistry, Pharmaceutical adjustment of the altered natural physiological processes that determine bone deposition and adsorption,[35] muscle growth,[36] and other critical physiological parameters will be the final line of defense that must be carefully examined. It is possible that such a defense will be necessary; however, until any potential long-term side effects of potential pharmaceuticals are understood or eliminated, this approach must be viewed with caution. On the other hand, modern research, led in large part by the NIH, continues to expand our knowledge of physiological systems in ways relevant to countering the adverse aspects of space adaptation.[37] Integration of terrestrial and space-oriented investigations offers much potential for the future.

13.2.2 Lunar habitats and spacesuits

We know a great deal about constraints on the design of habitats for humans in space and on the Moon[38] and will certainly learn more through continued occupation and refinement of the International Space Station. The probability is high that habitats can be designed and manufactured to be inflatable units, containing preformed, automatically deployable walls, wiring, and plumbing. For radiation and small meteor protection and thermal stability, habitats, as well as agricultural areas, will be enclosed by about 3 meters of regolith.[39] Coverage could be accomplished (1) by inflating habitats in trenches dug explosively or mechanically to near the base of the local regolith and with the roof then covered by excavated regolith, or (2) by inflating habitats on the surface and using exterior false walls or louvers to stabilize the regolith covering. A regolith blower or impeller may be the equipment of choice to direct regolith onto properly baffled roofs or into wall compartments. Alternatively, fluidized waste regolith fines might be piped into such compartments once mining and processing activities have been initiated (Chapter 7). Agricultural facilities also will require protection, with light pipes providing variable solar illumination as needed for various crops.

Natural light can be provided via light pipes, both for living quarters and plant growth areas. High-resolution, electronic windows, showing outside areas as viewed by video cameras, can provide real-time and realistic views of outside scenes and activities. As discussed below (Section 13.4), the prevention of dust penetration and damage will pose one of the greatest design challenges for lunar habitats.

Compared to the Apollo A7LB lunar spacesuit, the future spacesuit for a commercial Return to the Moon will need to be vastly improved in weight, mobility, and longevity. Weight of the combined pressure suit and personal life support system (PLSS or backpack) should be reduced by at least a factor of 2 by use of new materials and increased reliance on rover and exterior facility consumables. Using consumable sources outside the normal backpack will require vacuum connect and disconnect for oxygen and water as routine procedures. Mobility, particularly for the hand in the pressure glove, should be increased by at least a factor of 4. For the pressure glove, the goal should be to reach near normal, non-gloved mobility. Longevity, ease of maintenance, and reliability of spacesuits and backpacks will be particularly important to a commercial operation. They must be able to withstand heavy use in a very dusty environment and still be serviceable for at least the time between resupply missions, estimated to be between two and six months. Development of a spacesuit system to meet these requirements will require an integrated system of systems approach.[40]

13.2.3 Cultural and social adaptation

Cultural and social adaptation to permanent residence on the Moon will evolve over time.[41] In this regard, plans for the activation of a lunar settlement must provide a technological and managerial environment that is as flexible as possible in order to facilitate that evolution. This area of adaptation will encompass physical survival of the settlement and its population, the daily well-being of each individual, a framework for civil and criminal law, plans for continuing education and future schooling of children, desired religious activities, and social interactions.

As has been the case for human pioneers through history and prehistory, survival of the new settlement will be of primary consideration. Early polar and ocean exploration, and, indeed, current Antarctic habitation, probably give some of the best illustrations of the problems to be faced by early lunar settlers and possibly even some of the solutions. The experiences of the *Challenger*, *Beagle*, *Belgia*, *Endeavor*, *Endurance* and *Fram* expeditions of the nineteenth and twentieth centuries offer some of the best examples of both good and bad responses to the stress imposed on small groups of people working in confined and isolated conditions. Technological measures, including redundancy and backup systems, will provide the initial protection of the settlers. Individual responsibility and training relative to hazardous activities and situations, however, will be the principal insurance against catastrophic events or the consequences of their aftermath, should one occur.

Although useful work will be fundamental to the well-being of lunar settlers, a few important cultural considerations can be identified at this early date that will assist each individual in addition to the population as a whole. For example, settlers whose responsibilities do not allow them to partake regularly in activities outside the habitats and pressurized facilities can be expected to be subjected to various forms of cabin fever. Not only should there be regular opportunities for outside work and recreation, but the electronic video windows should show real-time views of exterior landscape and activities taking place therein. In addition, exercise facilities will be available as physical conditioning will be a mandatory requirement for all settlers as a primary countermeasure against any long-term adverse effects of adaptation to one-sixth gravity. When opportunities become available for temporary trips to Earth, preparation for one gravity re-adaptation will be particularly important.

Further, each individual should have a truly private area if so desired. Private video conferencing and e-mail contact with friends and relatives on Earth as well as elsewhere on the Moon also should be provided. Religious activities may take place through individual communication and private conferencing or may evolve as group activities with the growth of the settlement. A variety of individual and group entertainment and social options should eventually be available, including restaurants, theaters, and movies. With the advent of tourism, settlers will have access to lunar resorts and interaction with non-settlers. With an established lunar tourism infrastructure, settlers can consider taking vacations on Earth.

Opportunities for continuing education will be important to many settlers so that professional advancement and personal interests can be pursued. As some continuing education requirements will be identified for managerial advancements or job transitions, access to specific learning opportunities will be available through corporate sponsored entities. On the other hand, settlers will have access to an increasing variety of web-based, distant learning systems provided by many educational institutions. Additionally, as the settlement grows, interactions among the highly educated and experienced people of the settlement will create new opportunities for learning.

By the end of the first decade of the settlement's history, the need for the schooling of children will probably arise. Home schooling may be the initial method of meeting this need, but the settlers, following precedents set by American pioneers, may eventually decide to bring teachers to the Moon as additional permanent residents.

Over the long term, a framework for civil and criminal law will be required, given the inevitabilities of human nature and desires. Initially, that framework will be incorporated within the employment contracts of the settlers and the assigned management responsibilities at the settlement. Appeals of decisions made within this framework will probably be through remote communications, first with senior management on Earth, second through standard arbitration, and third through the terrestrial judicial system. Eventually, the settlers will need to determine a permanent, lunar centric system of civil and criminal justice.

13.3 SPACE RADIATION

Forms of cosmic and solar radiation constitute one of the principal hazards for which lunar settlers need to prepare.[42] Primary cosmic-ray particles consist of the atomic nuclei from elements ranging from hydrogen to iron in atomic mass with energies from 1 million to 150 billion electron volts. Secondary particles produced by cosmic-rays are dependent on the material encountered by the primary particles. Dangerous solar radiation is composed of ultraviolet light (UV), x-rays, gamma-rays, electrons, protons and various light element nuclei. By mass, protons make up 80% of the solar wind and helium nuclei another 18%.[43] Indeed, intense proton radiation during random solar particle events (SPEs), caused by coronal mass ejections from the Sun,[44] will be one of the more difficult hazards to protect against. As each solar particle carries an electrical charge (they are largely protons and electrons – that is, disassociated hydrogen atoms), the Moon's monthly transit through the Earth's protective magnetic field will affect their flux at the lunar surface. Development of a complete model for radiation at the lunar surface will require significant additional analysis.

Solar particle activity, normally not a major hazard, varies in intensity with solar activity within the 11-year sunspot cycle with SPEs occurring at various, apparently random times across this cycle. For example, the January 2005 SPE had energies of more than 100 million MeV.[45] Astronauts and cosmonauts on the International Space Station receive radiation doses of between 80 and 160 milliSieverts (mSv)[46] every six months.[47] NASA has set the annual limit for astronauts at 500 mSv with a lifetime limit at 2000–3000, depending on age.[48] The measurements by the Martian Radiation Environment Experiment (MARIE) on board the Mars *Odyssey* spacecraft[49] have indicated a background level near Mars of ~23 mrad/day or ~4200 mrad/six months or ~420 mSv/six months.[50] SPEs add, on average, 10 mrad/day for the month in which they occur although they are of only a few hours' duration. Background radiation on the Moon will be significantly greater than in the vicinity of Mars.[51] For comparison to these various figures, annual background on the Earth's surface is about 2 to 3 mSv and three chest x-rays give about 1 mSv. Doses of 25 mSv/six months are allowed by regulation for radiation workers dealing with various sources of ionizing radiation.[52] Clearly, protection must be provided against long-term exposures to radiation levels seen in the Space Station, not to mention higher levels at lunar distances. Conveniently, the Moon cuts essentially one-half of the radiation flux just by being the sphere it is. Inside habitats and other facilities, the provision for shells or covers of 2 to 5 meters of lunar regolith can provide protection from all forms of the remaining external radiation.

In addition to background radiation, major and extremely dangerous SPEs have been observed even near the solar minimum for sunspots, such as in August 1972, a few months prior to the Apollo 17 mission. For Apollo, these events were considered as part of the broad risk of exploration, comparable to the various, and often more serious risks faced by Lewis and Clark during the Corps of Discovery's transit to the Pacific Ocean. In contrast, radiation risk can be minimized for permanent settlers and future routine visitors, although uncertainties in the level of this risk are high.[53] A joint research program by NASA and the Department of Energy's Brookhaven National Laboratory aims at reducing these uncertainties over the next few years.

In the same way that I explored the valley of Taurus–Littrow during Apollo 17, people working outside protected structures will have spacesuits, helmets, and their internal cooling units to shield from normal UV and thermal radiation. While outside, however, there will be no shielding from some exposure to the more penetrating x-ray, gamma-ray and cosmic-ray background radiation. As more is learned about potential interventions with drugs to counter radiation effects,[54] regular, preventive treatment with such drugs may be appropriate, if they are shown to be both necessary and safe. On the other hand, persons working outside will potentially be exposed to solar particle events, warnings for which will only be on the order of half an hour.[55] After receiving such a warning, settlers must find or create protective shelter. In locations where activities take place on a routine basis, regolith-covered shelters can be pre-deployed. As the dangerous phase of particle events lasts only a few hours, pre-deployed shelters may be unpressurized and have oxygen, water, and power lines available for connection to spacesuits. Personnel working at a distance too great to reach a deployed shelter in the time available after a warning will have a lunar roving vehicle as support for a temporary shelter. Explosive excavation of a trench by a linear charge, with the rover placed over the trench as a roof, would provide a protected space. Additionally, deployable skirts on the rover sides and a small regolith impeller would allow for the rapid covering of this roof. Connections to consumables in tanks on the rover would provide support for the duration of the danger period.

13.4 DUST

Engineering and operational issues related to the invasive nature of lunar dust are discussed in Section 7.3. In addition, dust constitutes a potential human health hazard. Continuous exposure of lungs and other internal organs to micron- and submicron-sized mineral and glass particles, sizes too small to be cleared through normal processes, may cause long-term health problems. NASA has made no attempt to learn whether the Apollo astronauts' limited exposure to this dust has had any lasting effects or if normal body defenses protect against such effects. The latter appears to be the case based on long-term physical monitoring of many astronauts; however, research in this regard should be included in any overall effort to establish a program of lunar occupational health. Specific arrangements with local legal jurisdictions for targeted autopsies of surviving Apollo lunar astronauts should be part of that effort.

13.5 LUNAR OCCUPATIONAL MEDICINE

Space occupational medicine in general will require an integration of normal medical and preventive procedures in the work environment[56] with those specific to conditions in space. The practice of occupational medicine in reduced gravity and in the lunar dust and radiation environment, however, presents special challenges that have yet to be adequately addressed scientifically. Human responses to reduced gravity, and potentially other differences in the space environment from that on Earth, are systemic and highly individualistic. The integrated physiological basis for various responses to conditions in space is not understood. Although empirically there are few reasons to be concerned about long-term detrimental health effects, responsible healthcare for employees at a lunar settlement and helium-3 production facility requires the development of a credible scientific basis for occupational medical practice. Indeed, return to Earth for any form of healthcare will be a non-existent option until regular tourist flights begin. Business planning will need to include a systematic scientific examination of space adaptation syndrome and countermeasures to its adverse consequences, an examination that may lend itself to a cooperative private–federal research program.

13.6 FAMILY DEVELOPMENT

A prime objective of a private lunar initiative will be to establish permanent and ultimately independent settlements on the Moon, supported economically by resource production and services to scientists and tourists. To successfully complete the initial activation phase of helium-3 and other resource production on the Moon, however, the selection of settlers will be based primarily on skill and experience rather than on family development. Although couples will be selected over individuals, everything else being equal, family development and related issues will necessarily be subordinate to the technical requirements of establishing a permanent base of operations and production.

Once initial production capability has been reached (100 kg helium-3 per year), operational, habitat, and support margins will be added as appropriate to provide for children and other family-related needs. At that point, the following changes will occur:

- Additional personnel or comparable work schedule modifications will accommodate maternity leave and childcare requirements.
- Habitat additions or modifications will provide for family privacy.
- Prenatal and postnatal medical services will be assured by both on-site and remotely available expertise.
- Prenatal, postnatal, child and pre-adult physical therapy related to assuring normal development in a one-sixth gravity environment will be provided.

13.7 IMPICATIONS OF HUMANS IN SPACE

On January 14, 2004, President George W. Bush put his Administration squarely in support of moving civilization into the solar system and "into the cosmos." Left unstated in the President's challenge to NASA and the Congress is specifically how the roles of humans and robots will be balanced.

As a human explorer, I am excited about this new challenge to re-enter deep space. As an Apollo astronaut and geologist, however, I am offended by the uninformed treatment given to human exploration of the Moon and planets by a few, generally nameless, "space scientists."

Media reporters of these reactions should identify the "space scientists" that have had a "tepid response to President Bush's push to send astronauts to Mars."[57] I suspect that most of those interviewed are not field explorers, geologists or otherwise. Some may even have their NASA funding tied to robotic rather than human space flight. Others would object strenuously if removed from hands-on "exploration" for new knowledge in their own disciplines of science.

Further, most of these hidden critics apparently remain aggressively unaware of the extraordinary foundation of scientific knowledge about the origin and history of the Moon, Earth, planets, and Solar System that resulted from Americans exploring the Moon in person. This immense body of data and understanding could not be obtained by robotic exploration at anywhere near a comparable cost, and probably not at all. It constitutes the foundation upon which rests the interpretation of data from most post-Apollo and future robotic exploration of the Moon and terrestrial planets. Taking human explorers back to the Moon, to Mars, and beyond indeed may add "billions to the cost." To say, however, as some do, that it would add "not much in the way of discovery" shows an extraordinary ignorance of the unique scientific legacy of human exploration of the Moon and of over 150,000 years of modern human experience on our planet.

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IMPLICATIONS

RETURNING to the Moon for its helium-3 fusion resource constitutes the most predictable and potentially the most successful approach to rejuvenating humankind's migration into deep space. The future implications of this event are profound. Lunar helium-3 fusion power systems would become part of an indefinitely viable portfolio of clean sources for global electrical power generation and process heat, consisting additionally of Generation IV nuclear fission power plants, clean coal-burning plants, and local use of solar power technologies including wind power. Although it will be some years before a case by case determination of cost competitiveness can be made between these energy sources, all would appear to be in the running as regional if not global competitors. In addition to meeting the rapidly escalating demand for energy, this portfolio also would provide low-cost supplies of hydrogen as this form of stored energy becomes the world's principal fuel for automobiles and other forms of transportation.

The further implications of this transition in global energy availability over the next 50 years begin with a gradual increase in global political stability as each free nation can become dependent on itself rather than on others for energy. The implicit tyranny of unequal distribution of fossil fuels will disappear with access to low-cost electrical power through license, lease, or purchase. With ready supplies of domestic energy, nations with free economies and political systems can begin a rapid improvement in standards of living with a commensurate decrease in birth rates and eventual stabilization of populations.

This portfolio of fusion, fission, clean coal, and solar energy (including wind) also gradually reduces the addition of carbon dioxide to the atmosphere from human sources, cutting that particular contribution to natural climate warming trends. Whether future climate warms, or warms and then cools rapidly, more electrical power will be required to counter the adverse consequences of change, and this energy portfolio of the future can provide that power. Further, this portfolio significantly reduces the volume of radioactive waste that must be reprocessed or entered into long-term storage.

Not only will the economies of all free peoples benefit from the coordinated application of these future energy sources, but industrialized economies, particularly those of the United States, Europe, and Japan, will benefit from the competitive development of these technologies as well as technologies that can efficiently convert energy to useful purposes. Fusion and fission processes additionally will add the benefit of many applications in medical diagnostics and therapy. Free societies also will benefit from the many uses of fusion power systems and applied technologies to their national defense against terrorism and other potential threats from governments unwilling to participate in free society.

Finally, lunar helium-3 fusion, and selective applications of fission power, will open the Solar System to human exploration, settlement, and tourism. With this capability to venture at will into space, there comes the dual benefits of establishing the human species elsewhere besides Earth and of protecting the species' home planet from catastrophic impacts of asteroids and comets.

In spite of these long-term, positive implications of a Return to the Moon, it seems to some, upon hearing that a return is proposed, to be an unrealistic, misguided, and selfish effort.[1] Some engineers would say that the accomplishments of Apollo constitute an anomaly of a special time when risk was not an issue. Some policy makers would submit that such an initiative would detract from addressing more pressing national and global issues. Some social activists would say that the vast numbers of poor, hungry, and oppressed in the world deserve our attention far more than a Return to the Moon.

The preceding chapters present the case that all of these objections disappear if that return is put largely in the hands of private investors. The success of Apollo gives a private initiative the managerial and operational model that has been proven to work. The use of private capital, appropriately regulated by government and constrained by the Outer Space Treaty, relieves policy makers of choosing "space" over other needs. The availability of a new source of competitive, clean energy for growth in the world gives hope to the four-fifths of the world's population that, until now, depend on external sources of energy and must submit to less than minimal standards of living.

A successful private initiative to develop a commercial lunar helium-3 fusion option for global energy needs within the next 10 to 15 years makes possible a number of predictions. Twenty-five years from now there should be a permanent settlement on the Moon, with commercial operations producing helium-3 fuel for a growing terrestrial fusion electrical power industry. Hydrogen, oxygen, water, and food would also be produced for a second-generation, permanent International Space Station, partly operated by NASA as a research facility for the National Institutes of Health, the National Institute for Science and Technology, the European and Japanese Space Agencies, and other world-class research entities. Further, the Space Station would be an international tourist destination of significant excitement and broad financial accessibility.

Twenty-five years from now the United States and its partners should be in their fifth year of Mars exploration and permanent base selection. Activities related to Mars would rest on the relatively low-cost foundation of heavy lift boosters, fusion propulsion, facilities for indefinite habitation, and consumable resources available as continuous imports from the Moon. Further, with the availability of permanent production lines for heavy lift boosters, fusion propulsion systems, and interplanetary spacecraft, the Earth should have had 10 to 15 years of on-call protection from impacts of large asteroids and comets. These capabilities also should have provided 10 to 15 years of advanced options for global security, commercial space initiatives, and climate change mitigation.

Apollo bent our evolutionary path into the future. The psychological, technological, and survival bonds holding humans to the Earth have been broken. This new evolutionary potential in the Universe now permits us to live on the Moon and Mars. Generations alive today can determine if humankind will take advantage of this new status. Will we begin the settlement of the Solar System and provide for a "new birth of freedom" beyond the Earth? Placing the doubts behind us, let's continue the millennial adventure that began in 1969 and go where we have gone before, and then beyond (Figure 14.1). We owe the future of humankind another walk on the Moon!

FIGURE 14.1 The author walking in the Valley of Taurus–Littrow, December 15, 1972. (NASA Photograph 145 22165)

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