The Shackleton Crater Expedition:

A Lunar Commerce Mission
in the Spirit of Lewis and Clark

by

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November 2003

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Executive Summary

The space program of the United States of America is in disarray. During the past 30 years it has failed to deliver what the American public most wants from it: routine, economical access to space that enables broad private sector involvement and the establishment of a burgeoning extraterrestrial economy. The agency charged with this task, NASA, has instead woven an intricate partnership with its Cold War era subcontractors that has sought to maintain its Apollo legacy through a series of costly mega-projects lasting decades. These projects – the space shuttle and the International Space Station (ISS) – have failed. The shuttle remains an inherently dangerous vehicle for human space operations (and will remain so even following upgrades as a result of the Columbia investigation commission). But more importantly, the shuttle is non-competitive with alternative – particularly Russian – means for transporting goods to low earth orbit. The ISS, after 25 years of effort, remains incomplete and is presently capable of supporting just three individuals in orbit. Both programs cost the nation billions of dollars every year, yet produce no tangible forward progress towards the creation of an environment in which private sector space opportunities can flourish – and thus dramatically expand human presence off Earth.

It is the purpose of this proposal to illuminate a different path for the nation–one borne out of manifest destiny to perform sustained human exploration of the moon as a stepping stone to planetary commerce and improved national security. We postulate herein that, using predominantly off-the-shelf technology, but with a radically different execution plan, an Earth-Moon economy can be jump-started in five years with a budget of approximately $5 billion – an amount equivalent to 1/3 of NASA's budget for one year. The primary target of the proposed expedition will be the Shackleton Crater at the Moon's South Pole. Recent lunar orbiter spacecraft data strongly indicate the likelihood of the discovery there of all necessary raw materials for the creation of a positive return on investment (ROI), commodity-based Earth-Moon economy.

The year 2003 marks the 200th anniversary of one of the boldest, and most well-known exploratory feats in American history: the Lewis and Clark Expedition. Presidentially–mandated, and ultimately Congressionally–authorized and funded, Meriwether Lewis's undertaking to explore – for science, for commerce, and for nation building -- the extent of the newly acquired Louisiana Purchase was vastly different from the way in which we presently go about the business of space exploration.

There is much to be learned from the story of Lewis and of Jefferson that bears on our present situation with regard to space exploration. And in fact, it is exploration that is needed to break the present log jam that our national space program has become. Whatever this nation has done in low earth orbit during the past 30 years merely represents technology development and feats of men at sea in their ships. Exploration is more than that – it is the process of a human explorer placing footprints on terra incognita on the surface of or inside of another planet. Yet our present system (NASA) does not know how to achieve it within the budgets made available to it by Congress. Within NASA many still dream, yet they are tied to their "system" and within that system, they will never set foot on another planet again.

Consider, in contrast, the Lewis and Clark expedition. Jefferson rightly saw the exploration and exploitation of the American west as the key to expanding the nation. He thus seized upon the concept of the expedition and sold it to Congress – at a cost, ultimately, of almost 1% of the federal budget in 1803 ($17B in today's dollars). To ensure success, Jefferson issued Lewis a Presidential Letter of Credit, pledging the nation, such that the expedition could acquire any goods and services it needed. In effect, the Lewis and Clark expedition was a federally funded, independent entity to which all U.S. federal agencies, including the military, were commanded to provide services as requested. Importantly the Letter of Credit extended, without restriction, tariff or the like, to any foreign nation or company.

What the Lewis and Clark expedition did was to provide the crucial information that the frontier was in fact open and accessible and that there were commodities to exploit there. Those that followed in the pursuit of commerce along the route pioneered by Lewis and Clark opened the frontier that was to make America a world power. The opening of the path to Earth-Lunar commerce will be no less a feat and will have an equally powerful impact on the future of the nation and that of the peoples of Earth. Jefferson's instructions for the deliverables expected of Lewis and Clark are famous. An analogously bold set of instructions from President Bush would be as follows: Within five years and approximately$5 billion establish human presence on the moon to map natural resources and explore commercial opportunities. In particular, the team will:

- Demonstrate a sustainable, economical lunar polar exploration base by establishing a minimum 1 year and preferably <u>2 year</u> occupancy at a fully re-useable facility.
- Investigate the existence, access, and utility of lunar lava tubes for radiation, thermal, and micrometeorite shielding of permanent lunar facilities.
- Conduct scientific / biometric measurements of long-term lunar habitation through a non-intrusive, program to monitor the health of the expedition crew.
- Investigate the existence and accessibility of South Pole crater ice deposits at the Shackleton Crater (as suggested by the Clementine and Lunar Prospector orbiter missions).
- Demonstrate liquid oxygen (LOX) and hydrogen (LH2) production from water and regolith (lunar dust) and its subsequent storage on the moon.
- Investigate the feasibility of extraction and storage of solar hydrogen and helium-3 from lunar regolith.
- Return sufficient LOX and other lunar products (potentially including liquid hydrogen and helium-3) to LEO such that it will demonstrate the capability for a positive return on investment.
- Demonstrate low-cost systems for LEO-lunar cycling (that is, transport from LEO to the lunar base and back using fully re-usable vehicles)

The ultimate success of such an expedition would have enormous positive ramifications that will ripple across the coming centuries. It will represent the opening of an essentially unlimited new frontier (the inner Solar System) by showing the path to sustainable commercial extra-terrestrial ventures. The president that ultimately makes the expedition possible will establish for himself a place in history in parity with Henry the Navigator, Queen Isabella, and Thomas Jefferson. Such a feat would substantially exceed the political legacy of John F. Kennedy and the Apollo project.

The novel elements of the proposed expedition are as follows:

- Low Earth Orbit (LEO) rendezvous and assembly of a "fleet" of three lunar transfer vehicles based on a highly modular, redundant design that is inherently survivable (allows for field parts swapping).
- Inflatable spacecraft: both crew quarters & cryogen storage vessels constructed using foam-rigidized fabric that is deployed on orbit (this eliminates the requirement for new, large ELV boosters).
- High density (nuclear) long-life power systems for lunar base.
- Creation of return propellants on the moon (that is, the expedition travels to the moon without the fuel and oxidizer required for returning to earth – and will manufacture it on the moon).
- One-pass aerobraking for return-to-earth orbit capture and LEO rendezvous (this eliminates the vast majority of the rocket fuel that would otherwise be needed for this maneuver).
- Lunar-derived liquid oxygen and liquid hydrogen transported to LEO for subsequent missions (thus breaking the majority of the supply chain to earth); the surplus is for sale to interested parties.

It is important to remember that the principal goal of the proposed federally-funded expedition is to demonstrate to the private sector that there is a business case for establishing an Earth-Moon trade route –in effect, that there is a positive ROI potential. Trade studies included with this proposal indicate, clearly, that substantial profits can be made from this endeavor, despite serious up-front capitalization costs. Once demonstrated, industry can be expected to follow, but not before. Ironically, the best profit rate is achieved if the current launch systems for earth-to-LEO transport maintain the status quo, and thus increase the value of goods brought from the moon. Short of a major physics breakthrough, this status quo can be anticipated to exist for the next 50 to 100 years. Under this scenario, the missing piece, then, to bootstrapping human extra-terrestrial commerce is the establishment of a "railroad" to "mines" on the moon.

The availability of cheap (relative to earth-to-LEO supplied) lunar derived propellants in LEO will change the way spacecraft designers think for any vehicle intended for GEO and beyond. It will also be needed for any OTV (orbital transfer vehicle) that would be developed for servicing both high LEO and GEO satellite assets. And it is essential for "orbital makeup" and life support for the ISS, whose orbit is continuously degrading and must be periodically re-boosted. But most importantly, there is an immediate use of the system that would be demonstrated in the proposed project: that of lunar transport of people. At first, these would most likely be government–funded scientists and engineers desiring to conduct experiments on the moon. However, in the long run “high adventure” tourism would permit such a business to be self-sustaining and expand, gradually making the experience available to greater and greater numbers. The availability of "cheap" hydrogen, oxygen, and water in LEO will also add considerable fire to those companies now striving for commercial Earth-to-LEO space tourism, for it will be enabling for the maintenance and operation of commercial facilities (hotels) in LEO.

In conclusion, we recommend the establishment and funding of a Presidentially-appointed Joint Lunar Expeditionary Program Office (JLEPO) to lead the expedition planning and execution. Initially this office should be charged with answering the six questions posed by the expedition:

1) How will the JLEPO be organized and managed? It should be structured as a national program with support provided by appropriate departments, agencies and offices.

2) Are there any technical show-stoppers?

3) Is the budget realistic?

4) How will legal issues be dealt with (e.g. bypassing tariffs on the use of foreign boosters etc.)

5) What is the best fiscal-institutional structure for the expedition (non-profit corporation; military expedition etc.)

6) What should be the makeup and nature of the crew needed to carry out the expedition and under what management structure should it function?

The Program Office would charged with presenting the findings along with a recommended plan to the President for making the Shackleton Crater Expedition an Executive Initiative .

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Introduction:

The year 2003 marks the 200th anniversary of one of the boldest, and most well-known exploratory feats in American history: the Lewis and Clark Expedition. Presidentially mandated, and ultimately Congressionally authorized and funded, Meriwether Lewis's undertaking to explore – for science, for commerce, and for nation building -- the extent of the newly acquired Louisiana Purchase was vastly different from the way in which we presently go about the business of space exploration. There is much to be learned from the story of Lewis and of Jefferson that bears on our present situation vis a vis space exploration. What ultimately came to be called the "Lewis and Clark Expedition" was conceived of and planned by Thomas Jefferson himself, as a mechanism for the expansion of American influence to the Pacific. The degree of it's ultimate success has been marked by historians as one of the three great accomplishments of Thomas Jefferson[1].

This past year has been marked in stark contrast by controversy and tragedy in the space arena. The Space Shuttle Columbia's disintegration during re-entry and the inevitable investigation that followed it has brought American civil space endeavors to a halt. Optimistic NASA officials indicate the Shuttle will fly again in six months; others more conservatively predict as much as two years before operations resume. Meanwhile, the $40B+ international space station orbits idly. Incomplete, and with a gradually decaying orbit, alternative methods of re-boost must now be sought[2]. Thrusters onboard the ISS could be used for this purpose, but the primary issue is one of fuel, which must still be transported to the ISS from earth.

The public, meanwhile, has undergone a slow, inexorable estrangement from the U.S. space program that began not with the Columbia, nor even the Challenger tragedies. The American public's disaffection with the American civil space effort had its roots in the post-Apollo era when the dream -- that this nation would continue a steady and purposeful path towards opening the final frontier to <u>them</u> -- slowly evaporated in the face of the realization that the status quo would be maintained. And indeed, it was not even a status quo, for congressionally mandated funds for civil space endeavors have in fact declined or remained flat for each of the years following the conclusion of the Apollo program in 2003 normalized dollars. The use of a small corps of government-selected individuals[3] to accomplish the Cold War feat of landing men on the Moon before the Russians had been accepted at face value. But underneath, most Americans felt that the very next objective would in fact be the opening of space to commerce, travel, and

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[1] The other two being the Northwest Ordinance of 1787 that made provision for the conversion of western territories to States when their population reached a certain level; and the Louisiana Purchase from Napolean.

[2] Up until the demise of Columbia, orbital decay of the ISS was made up by delta-V burns from the docked Space Shuttle OMS engines; negotiations are underway with the Russians presently to develop a means for providing this velocity make-up using either Soyuz or Progress systems.

[3] That is, the Astronaut Corps.

the like[4]. Success meant developing means to radically reduce the cost of access to space[5]. The troubled history of the Shuttle development and operation program – driven technologically by the militarily-imposed requirements of cross range and horizontal landing -- followed by the 25 year design, development, and partial assembly of the ISS, all at a cost in excess of $150B, underscore the abject failure of the present system to deliver the goods. From an exploration standpoint it is also important to recognize that none of what NASA has done in the past 30 years, constitutes exploration[6]. Whatever this nation has done in low earth orbit during the past 30 years merely represents technology development and feats of men at sea in their ships. Exploration is more than that (see footnote 4). Yet our present system (NASA) does not know how to achieve it within the budgets made available by Congress. Within NASA many still dream, yet they are tied to their "system" and within that system they will never set foot on another planet again.

What's Broken and How to Fix It:

There are many reasons for the present state of affairs in the civil space arena, but four are worth discussing in detail here for it is in understanding them that a completely different path forward may be found to break the log jam we presently face as a nation and as a species seeking to be truly space faring explorers.

1) The Obsession with Risk Elimination

In a recent issue of Aerospace America, Jerry Grey states matter-of-factly: "The long-feared but not unexpected loss of a second shuttle orbiter is now a sad chapter in the history of the U.S. space program. As with Challenger 17 years ago, none of us will ever forget the brave crewmembers who lost their lives when Columbia disintegrated as it was making its way home on February 1. And once again as with Challenger, the tragic loss will have a major impact on the future of U.S. civil space flight."

The just-released findings of the Columbia accident commission confirm Grey's fears. Although the commission acknowledges the risks of space flight it then devotes the remainder of the

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[4] Recent, extensive polling has placed the enabling of personal travel to space as holding the highest priority to the average citizen, when compared among other possible activities that could be undertaken in space by the nation.

[5] It is useful to break down space-related activities into three separate categories: a) earth to LEO transport; b) permanently orbiting and extra-terrestrial (e.g. lunar bases) infrastructure; and c) return-to-earth systems. These need not be provided by the same space vehicle.

[6] In the context of all that follows we are referring to human exploration – that is, the process of a human explorer placing footprints on terra incognita on the surface of or inside of another planet. While we do not discount for a second the great accomplishments that have been made and continue to be made through the use of intelligent mechanical scouts (robotic spacecraft) these must be viewed in perspective as merely adjuncts and pre-cursors that pave the way to human exploration where practically feasible. Restated bluntly: robots are the tools human explorers and scientists will employ from now on for the investigation of places that are not suitable, practical, nor efficient for human exploration due to the presence of truly hostile or lethal environments as well as for the initial reconnaissance of places presently too-remote owing to our limited propulsion technology. Robots are not, and never will be, a substitute (even if viewed as a cheap, low-risk alternative) for human exploration simply because it is in the nature of homo sapiens to be curious, to explore new worlds. A raster line sent by a robot to a remote monitor, however exciting to see for the first time, is no match for the experience of actually being there, on that remote planet and experiencing it in person. Aside from this purely philosophical argument, robots presently are likewise no match for human dexterity, image processing, and real-time reasoning and therefore cannot exploit exploration and scientific related clues that human instinct would naturally detect.

document to discussion of the failings of NASA to eliminate such risk. Exploration – real exploration – is, by its very nature, hazardous. The White House and Congress of today would do well to read a brief summary of some of the most historical voyages of exploration in the past 500 years. In an era when the global human population numbered less than 100 million, exploration crews would suffer 40% loss rates (fatalities, that is) during the course of a two or three year mission. Some of these would die from disease, some from malnutrition, some from storms, some from hostile natives, some from mechanical malfunction of their seagoing vessels. There were no state funerals for these crews. No national mourning.

As a peculiar consequence of the Cold War, astronauts were elevated to the status national heroes. This status has persisted – in large part fostered by NASA for political gain -- despite the conclusion of the Cold War. Thus, when astronauts die, it becomes a matter of the nation. Investigations follow. Blame is assigned. And institutions fret over how to "change the system." Consider, in contrast, that in the Golden Age of terrestrial exploration (1500-1800), new boats were built, new crews staffed, and the next mission carried out, regardless of the previous loss. They all knew that the rewards were worth the risk. Fixation with risk elimination drives program costs upwards and delays mission completion, sometimes interminably. Consider by comparison the lack of national attention given to a general aviation tragedy – where not 7 but several hundred individuals die. Investigations follow, true. But the result is generally rapid re-engineering with flights resuming in a short period of time. Quick solutions are required because society has integrated a requirement for air travel into its economy. The above should not be construed to support reckless abandon with regard to national space efforts. Rather, it is to provide a mirror on the nation that our present posture of risk elimination is incompatible with the nature of exploration. The key is to design systems such that they are simple enough to be inherently survivable and economical enough to be accessible by a broad sector of society. Such designs will not look like the space shuttle. The nation should be prepared from the start to accept the fact that individuals may well die during the course of the proposed mission. The challenge will be designing the infrastructure and choosing the team such that there is a high likelihood of successful mission completion, even in the face of potential fatalities.

2) The Jobs Program Syndrome:

During the zenith of Apollo NASA was an extraordinarily effective organization for the same reason as the Manhattan Project. It was able to, under enormous time pressure, successfully carry out a clearly defined mission of compelling national importance in an effectively unlimited budget environment. The political circumstances that led to those two projects are historical and have not existed since 1972. Yet, NASA continued forward as if they were still in place. It had, under Apollo, constructed massive facilities, established eight major national research and operations centers, and employed a huge staff of federal employees. Rather than downsize post-Apollo (a common practice in industry) NASA sought to invent means to retain and focus the staff on new Apollo-scale projects that lasted decades. The first such program was the space shuttle; the second what ultimately came to be called the International Space Station (ISS). It is useful to note that the time from initial concept to successful mission completion for Apollo was less than 7 years; for the shuttle it was approximately 10 years; for ISS: 22 years. It is important for the reader of this proposal to understand the following reality: it is <u>not</u> in the interests of NASA, nor any of its long-time aerospace-industrial complex partners, to invent cheap, simple means of doing things in space, because the development of such solutions would spell the political destruction of the organization and its job machine (see topic 3 below for examples). Reducing the size of NASA and making it more efficient will prove as difficult as military base closings.

3) The Not-Invented Here Syndrome

NASA is notorious to "outsiders"[7] for its resistance to novel concepts that are inherently at odds with its internal long-term roadmap and its long-term survival as a federal institution (see item 2 above). One particularly illustrative example (of innumerable anecdotes known to many) will serve to drive home the point. Shortly following the first successful launch of the space shuttle many bright engineers made the observation that even though the shuttle had been billed as a "reusable" spacecraft, fully a third of the volumetric infrastructure that comprised the launch vehicle was thrown away on every launch[8]. This "expendable" third is, of course, the external tank – the orange-colored, bullet-shaped storage vessel for the liquid hydrogen and LOX used to fuel the three shuttle main engines during launch. During most nominal launches this tank reaches 99% of orbital velocity before being intentionally ditched (re-entry is typically over Hawaii, ¾ through the first orbit). The tank is, structurally, capable of supporting internal pressures sufficient for human habitation. Among many uses, it could be used as a low-cost, shirt-sleeves industrial laboratory or commercial facility if purged on orbit and pressurized with a breathable atmosphere. Calculations and design studies were performed by numerous technically-qualified -- but importantly non-NASA -- organizations that indicated the tanks could be safely boosted into LEO post-MECO[9] and stabilized there for long-term industrial use. The E-tank manufacturer, Lockheed-Martin, had even suggested a concept of an aft attachment to the E-tank that would serve as a small orbiting laboratory. One commercial and one institutional organization signed MOUs with NASA to pursue the storage of E-tanks in orbit. But these efforts were stalled through an endless series of bureaucratic barriers constructed within NASA. Only then did it become apparent that an E-tank in orbit represented a threat to the ISS: the E-tank held more than 10 times the internal pressurizable volume of the ISS and it was effectively "free" with every launch. High officials at Martin – who had initially lauded E-tank development efforts -- lamented privately that they would no longer pursue any dual-use activities relating to the E-tank, lest that posture lead to cancellation of its lucrative E-tank manufacturing contract. The ISS continued on, then, un-opposed, as the only pressurizable, human orbital habitation being planned.

Similar situations have arisen within NASA with regard to emergency escape from orbit (aka the "Assured Crew Return Vehicle" or XCRV, and novel private sector low-cost alternatives); space suit designs (notably the cancellation of the novel Ames AX5 program due to internal turf wars with JSC); ecological life support systems (initiated privately by Space Biospheres Ventures, Inc., later investigated at JSC in a program known as "BioPlex" and then cancelled); and inflatable spacecraft (originally proposed by Lowell Wood and associates at Lawrence Livermore as a cheap alternative for Mars mission spacecraft; initially denigrated by NASA,

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[7] i.e. those who are not NASA employees nor among those who work for major NASA contractors.

[8] In terms of cost per kilogram to LEO, the space shuttle external tank represents an on-orbit asset worth at least $500M.

[9] Some common space acronyms: LEO: Low Earth Orbit; MECO: Main Engine Cut Off, the point, almost in orbit, where the shuttle separates from the external tank and thence uses the OMS (Orbital Maneuvering System) engines to achieve its final orbit. It is a little-known fact that the shuttle could directly proceed to orbit with the external tank attached and that doing so would offer no penalty in terms of mission success on most shuttle trajectories.

which then quietly, several years later, conducted experiments with an inflatable attachment to the ISS known as "TransHab"; and then abruptly cancelled the program) to name a few. Both of the latter programs were terminated due to ISS cost over-runs and the need for internal fiscal re-programming at NASA.

Despite these shortcomings it is important to recognize that within NASA there remain pockets of extraordinary engineering expertise – in propulsion; materials; guidance, navigation, and control; avionics; life support and environmental control; radiation and debris modeling; communications; space power systems; computational fluid dynamics; atmospheric re-entry and hypersonic design and simulation; fuel storage; in-situ resource processing, autonomous systems design and more. This vast technology base would be extraordinarily useful, as needed, to any alternatively-organized endeavor to conduct a long-duration expedition to the moon. Below we discuss the nature of that alternative organization and the radically different design and execution approaches it would take to economically establish a permanent human outpost on the moon.

4) The Heroic Mission Syndrome

Not long ago a senior NASA delegation went to the National Institute of Standards and Technology (NIST) to present its technical case for a mission to Mars. During the course of the two day briefing a number of ambitious technology development projects were described that were underway in support of the mission. The delegation then turned to the issues of mission execution, timeline, and budget. The overall mission was to last nearly three years (accounting for the lengthy outbound and return trip to Mars) and cost on the order of $150B. The most striking aspect of the mission from an exploration viewpoint, however, was the crew complement and the total time actually spent on the surface of Mars for this investment. The crew size was limited to four, one of which would remain in Martian orbit tending to the earth-return vehicle while the remaining three would descend to the surface of Mars where they would spend 21 days collecting data and samples. Simple math produces the following astounding fiscal fact: during the productive time spent by the expedition (when the crew is actually on the surface of Mars doing something, not sleeping, eating, or gearing up that is) the mission cost to the United States of America is $83,000 per second per person. Explorers on Earth not involved in the space program have long recognized one important fact: one does not accomplish significant commercial and scientific objectives on a mission in which the transit time to the area of interest comprises 98% of the mission duration. In fact, the most productive expeditions seek to invert this figure with 2-5% of the time spent in transit and 95 to 98% of the time spent on site doing productive work. Only a politically-motivated mission can tolerate the former. When one analyzes the Apollo program with cold scrutiny we find that exploration and commerce were not the mission; placing national heroes on the Moon and returning them safely to Earth was the political mission. In that context, the actual time spent on the surface of the Moon was constrained only by the measure of "was it a sufficiently long a time to demonstrate that the national will of the United States of America was superior to that of the Soviet Union?" A day or two was deemed sufficient in 1972. Three decades later Apollo-era mission planning was still in effect and 21 days were apparently considered sufficient for Mars. In the proposal described below it is the commercial content of what is to be done on the Moon that will determine mission success. In this context, we must return to the traditional philosophy of terrestrial expeditions: amortize the expense of the transit by setting up a long duration base that remains in use until insitu exploration and material exploitation has shown commercial profitability. Such a mission will require an on-site stay on the order of years, not hours or days.

Those who participate in the mission will be "industrial" astronauts, not national heroes. They will be a different breed from the shuttle and ISS astronaut corps – hardened to the concept of being alone, self-contained, and self-dependent on an alien world for years. And this, too, is a necessary step forward.

Organization: The Lewis & Clark Model and the Jefferson Presidency:

We seek here to present an alternative to the long-term exploration and exploitation of the moon and to the establishment of commercial and industrial facilities in LEO that would make profitable use of lunar-derived materials and resources. The Lewis and Clark Expedition model provides a clear contrast to how we presently take on space-related activities. We examine below the key facets of the 1803 expedition:

1) Presidential Mandate:

Thomas Jefferson was obsessed with an all-water route to the Pacific. His thinking along these lines is captured best in Undaunted Courage, by Stephen E. Ambrose:

> "Rivers dominated Jefferson's thinking about North America. For the immediate future, he was determined to get control of New Orleans for the United States, so as to prevent the West from breaking away from the United States. Beyond that, he sought an all-water route through the unexplored western two-thirds of the continent"… to the Pacific.

The underlying philosophy that fueled Jefferson's notion lay in the need for expanded access to land, largely for agricultural, and in particular tobacco, interests, since these formed a large component of the U.S. economy in those days. The analogous commodity in 2003 is energy, and it is this aspect of lunar-derived resources that will dominate the earth-moon economy in the coming years.

Stephen Ambrose continues:

> "In the decade following the winning of independence, there were four American plans to explore the West. Jefferson was the instigator of three of them." All failed to achieve the necessary funding."

The catalyst that changed this was the Alexander Mackenzie expedition (British) from Canada. Mackenzie discovered the river that bears his name as well as land passage to the Pacific through northern Canada. The news of this discovery had electrifying effect in Washington, as historian John Logan Allen reports in his book Passage through the Garden: Lewis and Clark and the Image of the American Northwest:

> "Mackenzie said in effect that 'the way to the Pacific lay open and easy'… it was this simple fact of imaginary geography that gave birth to the Lewis and Clark expedition…. Jefferson made his decision sometime in the fall of 1802 that there would be an American answer to Mackenzie and that Lewis would lead it."

Thus, one important facet of the Lewis and Clark expedition was that it had presidential backing from the very start. Although the budget analysis at the end of this proposal indicates that the project we propose could in fact be funded by extraordinarily wealthy individuals it is unlikely that such funds will be forthcoming due to the high risk nature of the endeavor. As with Lewis and Clark, once the path has been blazed and the mechanisms for exploitation illuminated, one can then anticipate with some measure of assurance that now, as 200 years ago, speculators (venture capitalists) will emerge to enjoin the endeavor… but not before.

2) Congressional Funding and Jefferson's Presidential Letter of Credit

The Lewis and Clark expedition was a federal endeavor. Although Jefferson initiated and backed the idea personally he did not by any degree have the capital to fund it himself. He therefore privately approached select members of Congress. Ambrose continues:

While "Lewis drew up an estimate of expenses, to present to Congress as part of a request for appropriation, Jefferson began to widen the circle of those who knew about the proposal. Initially the expedition was to consist of an officer and 12 soldiers."

So, what, then was the budget for the Lewis and Clark expedition? The Senate Executive Journal (437-39) of January 18, 1803 notes:

Thomas Jefferson sends a secret letter to Congress asking for "the appropriation of two thousand five hundred dollars, for the purpose of extending the external commerce of the United States." This money will be used to fund the Lewis and Clark Expedition.

Congress approved. On February 28, 1803 the Annals of Congress, 1565; Statutes at Large, volume 2, 206 report:

Thomas Jefferson signs into law "An act for extending the external commerce of the United States," which appropriates $2,500 for the Lewis & Clark Expedition.

However, this was not to be the total cost of the expedition, only the beginning. The actual field expenses were as unknown as the terrain to be explored. To this end, Jefferson wrote a Presidential Letter of Credit which Lewis was to carry with the expedition, as reported by Stephen Ambrose:

"That same July 4th, the president gave to Meriwether Lewis a letter authorizing him to draw on any agency of the U.S. Government anywhere in the world anything he wanted for an exploring expedition to the Pacific Ocean. He also authorized Lewis to call on 'citizens of any nation to furnish you with those supplies which your necessities may call for' and signed 'this letter of general credit for you with my own hand.' Thus pledging the faith of the United States government. "

It is crucially important to note here that Jefferson's letter of credit extended to foreign nations and carried no baggage, tariffs, trade, or technology restrictions. In the language of today this meant: no sole-source justifications, no publication in FedBizOps, no ITAR restrictions, no small business set-asides, no tariffs or other industry-protection levies, and no local, state, or federal sales or property taxes on any expedition-related expenditure. Lewis was authorized to directly procure whatever he needed to make the expedition succeed.

From April 1803 through October 1807 (the generally recognized inclusive dates of the expedition, which included the planning and post-expedition documentation stages) the total expenditures looked like this:

Original appropriation:	$2,500	
Additional field expenses:	$38,722	
Compensation of the team (post-expedition):	$11,000	(mainly salaries and land grants)

Return of Big White to the Mandan Tribes[10]:	$7,000
Total:	$59,222

At the time this was considered an extraordinary expenditure and Congress debated the payment for two months before ultimately authorizing closure. The entire federal budget of 1803 was $7,852,000[11]. Thus, the Lewis and Clark expedition cost the federal government 0.8% of the federal budget for one year. What would this represent in present-day funds? There are many ways to calculate the inflation, but probably the fairest comparison would be to use the percentage of annual federal budget, since it was just as painful to fund a federal project in those days as it is today. The projected U.S. federal budget (OMB) for FY 2004 is $2,229 billion. In today's dollars then, the Lewis and Clark expedition would cost the nation $17 billion. This is approximately equal to the FY2004 NASA budget request.

3) Explicit Instructions to Federal Entities & Foreign Governments

At the time of the Jefferson Presidency, the following comprised the cabinet: Vice President, Secretary of State, Secretary of the Treasury, Secretary of War, Attorney General, Secretary of the Navy. It was the institutions headed by these individuals to which Lewis would turn primarily for the materiel and personnel needed to conduct the expedition. An important facet of the expedition was Jefferson's letter of instruction to Lewis on the objectives of the mission:

"The expedition authorized by the popularly elected Congress would combine scientific, commercial, and agricultural concerns with geographical discovery and nation-building. All the pillars of Enlightenment thought, summed up with the phrase "useful knowledge", were gathering in the instructions" from Jefferson to Lewis.[12]

Tersely summarized, Jefferson commanded Lewis to:

- investigate commerce potential of the Louisiana Purchase (specifically the upper Missouri)
- determine the extent of navigable waterways (and in particular to find a connection between the upper Missouri and the Columbia)
- determine conditions for farming and ranching
- determine the existence and extent of mineral resources
- determine the presence of native tribes and whether they are friendly[13]
- map the new territory
- document the new discoveries (including flora and fauna) in a detailed log

An analogous set of mission objectives will be presented below for a lunar commerce expedition.

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[10] The expedition had made good use of the Chief of the Mandan Indian Tribe, Big White, for safe negotiation of the Missouri and the chief had accompanied the expedition on its return to St. Louis. Eventually, a separate expedition, paid by then Governor of Louisiana Lewis, had to be fielded to return the chief, as well as to begin the exploitation phase (mainly fur trapping) of the region by Americans. This final expense must fairly be attached to the total cost of the Lewis and Clark expedition.

[11] From Historical Statistics of the United States: Colonial Times to 1970, published by the U.S. Census Bureau

[12] From Undaunted Courage, by Stephen Ambrose

[13] In actual fact, a detailed checklist was prepared for assessment and cataloging of the native tribes, including their religious beliefs, customs, mannerisms, language, the extent of their territory, and their allies and enemies.

4) Mission Organization

Meriwether Lewis was a captain in the U.S. Army at the time of his assignment[14] to command the mission. His co-leader, William Clark, was also a captain in the army[15]. Since there was a near certainty of encountering hostile natives at some point during the expedition the merits of a military versus private citizen personnel complement was discussed at length. Ultimately Jefferson decided that it should be a small, non-provocative military team augmented by civilian translators, guides, cooks, animal managers and the like. Jefferson recognized the merits of a military hierarchy of enforceable authority in a multi-year expedition where discipline in the face of adversity was a prerequisite. Nonetheless, all members of the expedition were volunteers. Lewis was granted absolute authority on the hiring (all members were paid, with promises of additional land grants) and dismissal of crew members who failed to perform or who proved to not fit in with the team. Lewis ultimately shared this authority with Clark, but this is by no means an historical commonplace; most expeditions work best with a single, strong leader who commands respect not by mandate, but through deed.

5) Public Results of the Endeavor and Lessons for the 21st Century

It is useful here to emphasize the astounding importance of the publication of the logs of the Lewis and Clark expedition. No less than Henry Adams reports, in his History of the United States of America During the Administrations of Thomas Jefferson that:

> "…great as were the material obstacles in the path of the United States, the greatest obstacle of all was in the human mind. Down to the close of the eighteenth century no change had occurred in the world which warranted practical men in assuming that great changes were to come"

What the Lewis and Clark expedition did was to provide the information that the frontier was in fact open and accessible. And those that followed in the path of commercial exploitation of the route pioneered by Lewis and Clark opened the frontier that was to make America a world power. The opening of the path to Earth-Lunar commerce will be no less a feat and will have an equally powerful impact on the future of the nation and that of the peoples of Earth. Just as Adams warned two centuries ago, today we are stuck in the syndrome that space can be opened by only one means: through the agency known as NASA. It is high time for out-of-the-box thinking.

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[14] In fact, he was promoted to Captain by Jefferson to facilitate Lewis's leading the expedition.

[15] A retired captain; he was re-instated at the rank of Lieutenant for the purpose of the expedition. Lewis treated him with equal rank.

A Proposed Expedition to Shackleton Crater (2003-2008):

Much as Jefferson's instructions to Lewis were explicit in the results that were expected to be returned, we list here, tersely, the analogous objectives for a bi-centennial Lewis and Clark expedition to the moon. Each of these resolves a major question that bears on the viability of Earth-moon commerce:

Human Exploration:

- Demonstrate a sustainable, economical lunar polar exploration base by establishing a minimum 1 year and preferably 2 year occupancy, at a fully re-useable facility.
- Investigate the existence, access, and utility of lunar lava tubes for radiation, thermal, and micrometeorite shielding of permanent lunar facilities
- Conduct scientific / biometric measurements of long-term lunar habitation through a non-intrusive, rational program to monitor the health of the expedition crew.

Commercial Exploitation:

- Demonstrate liquid oxygen (LOX) production from regolith (lunar dust) and its subsequent storage on the moon
- Investigate the feasibility of extraction and storage of solar hydrogen and helium-3 from lunar regolith.
- Investigate the existence and accessibility of South Pole crater ice deposits at Shackleton Crater[16].
- Return sufficient LOX and other lunar products (potentially liquid hydrogen and helium-3) to LEO such that it can be sold and ultimately fetch a handsome profit
- Demonstrate low-cost systems for LEO-lunar cycling (that is, transport from LEO to the lunar base and back using fully re-usable vehicles)

Of these, the last two clearly represent the commercial segment “bottom line” that will demonstrate the potential for a positive return on investment that the commercial sector will seek before committing its own resources to the Earth-Moon economy of this century. Each of these topics is discussed in detail in the Expedition Logistics section below. But before that, the topic of presidential leadership and strategic decision making must be addressed.

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[16] This is the expedition's namesake for several reasons. The most compelling reason is that three sources of data relating to the polar regions of the moon (the Clementine lunar orbiter mission of 1994; the NASA Lunar Prospector orbiter mission of 1999; and earth-based bi-static radar studies) have all indicated a strong likelihood of concentrated deposits of hydrogen – most likely in the form of water ice or solid ammonia) within the 30 kilometer diameter Shackleton Crater at the Moon's South Pole. The confirmation of substantial deposits of either of these hydrogen-rich substances in Shackleton Crater (or other lunar polar craters) would represent an historic breakthrough that would presage the opening of the Inner Solar System to humans. Secondarily, within ten kilometers of the Shackleton Crater rim there is a point known as the "Peak of Eternal Light" where solar power would be available 98% of the year – an important factor for base establishment in the event that space auxiliary nuclear power were to prove politically untenable. The success of the current NASA/DOE Prometheus Program will likely determine feasibility of a nuclear solution and should be vigorously funded.

How President George W. Bush Can Secure His Place in History:

Partisan political analysis aside, the first three years of the Bush presidency fail to place him in a positive historical light. The response to terrorism and the controversial invasion of Iraq are not the material of outstanding presidential legacy – for they are in large part reactive, not proactive, and represent the expenditure of enormous sums of public funds for which the public benefit is at best unclear. What President Bush needs is a proactive, highly visible, cost-effective project that inspires all humanity in a positive fashion and advances the human cause in a manner that all will agree, now and in the future, that this was a great thing to have done. The advancement of human exploration but more importantly self-sustaining, profitable industry beyond Earth, is such a non-partisan vehicle.

Yet, as many recent presidents -- including George Bush Sr. -- have learned, pointing their finger at the stars following yet another NASA initiative report has led to naught during the past 20 years. It is not unlike the three failed initiatives that Jefferson led prior to the successful Lewis and Clark expedition. The preceding discussions illuminate the path to success in this arena: presidential leadership; an expeditionary organization independent of the existing federal apparatus; explicit instructions to federal departments and agencies to provide service as requested; and a presidential letter of credit upon which the expedition could draw upon for purchases of goods and services from both U.S. **and** foreign sources. These factors were the powerful enablers of the ultimate success of the Lewis and Clark expedition. In 2003 this would translate bluntly to the following important underpinnings of a successful long-term lunar exploration mission:

- A fixed five-year budget, guaranteed by congress[17]
- Explicit instructions to federal departments and agencies, including the military, to promptly provide to the expedition whatever services are requested by the expedition (whose services would be paid for by-the-barrel from the expedition coffers at reasonable rates). In the case of NASA this would include, as well, direct orders to provide free, unrestricted access to the ISS for expedition staging and housing of expedition personnel in LEO[18]. It might also include an explicit NASA role as technology provider, subsystem provider, and a sub-mission provider -- e.g. by planning and carrying out the robotic mission precursors and also by using the existing astronaut corps, shuttle, and ISS to help prepare the expedition for departure from LEO, from which point the independent expedition authority would depart.

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[17] It is estimated that three years from the date of initiation of funding will be required to design, procure, and assemble in LEO the necessary hardware and to train the necessary personnel to the point that a 2-year lunar mission can be successfully conducted.

[18] Although the space shuttle could be used to transport expedition assets to the ISS for assembly it must be stated that there are much more cost-effective options available (see Appendix B). These less expensive solutions (e.g. the Russian Proton) are required to achieve the proposed budget; if an "all American" solution is considered essential and Congress sees the shuttle to be a part of that, then the overall mission price will rise dramatically. Alternatively, since the shuttle and ISS are "sunk" costs, one could remove the cost of providing these goods and services from the proposed mission, which could then be thought of as departing from the ISS. This would dramatically reduce the budget herein proposed.

- Notification to foreign governments that a letter of credit has been issued to the expedition that authorizes it to freely and directly purchase goods and services from those governments and corporations residing in those countries without restrictions should the expedition determine this to be necessary to keep the project within budget and on schedule.
- Immunity from federal, state, and local procurement regulations.
- Immunity from federal restrictions and tariffs on the use of foreign, particularly Russian, launch vehicles and other space-related hardware acquisition.
- Immunity from ITAR restrictions.
- Immunity from federal, state, and local restrictions on crew selection, hiring, and potential dismissal.
- Granting of open-ended launch and re-entry licenses for all expedition-related transport as well as authorization to transport portable nuclear power sources to Low Earth Orbit (LEO) and on to the moon[19].

The cost of the expedition (see Appendix A), if the above factors are in place, will amount to about $5 billion[20]. The dramatic economies projected are both the result of the above fiscal organization points as much as the novel technology described below. The form of the expeditionary entity to enable the above foundation points is something that will require legal analysis. It is conceivable that a private, not-for-profit corporation – commissioned by the government in much the same fashion as COMSAT was in the 1960's -- could be formed with personnel (whether military or civilian) assigned to the corporation for the duration of the expedition. This organization would be a "federal space corporation" free to operate in any state within the United States and immune from federal, state, and local taxation. The organization could either be dissolved following completion of the mission, or maintained to manage the lunar and LEO assets it has created in such a fashion as to encourage industry investment in expansion of the established LEO-moon infrastructure. In the Conclusions section below we offer explicit recommendations to the President needed to initiate the endeavor.

The ultimate success of such an expedition will have enormous positive ramifications that will ripple across the coming centuries. It will represent the opening of an essentially unlimited new frontier (the inner Solar System) by showing the path to sustainable commercial extra-terrestrial ventures. The president that ultimately makes the expedition possible will establish for himself a place in history in parity with Henry the Navigator, Queen Isabella, and Thomas Jefferson. Such a feat would substantially exceed the political legacy of John F. Kennedy and the Apollo project.

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[19] See the later discussion regarding power needs of the expedition. All analyses thus far conducted point to an inescapable requirement for a 50-75 kW continuous electrical power source that will operate for decades – something that cannot reliably nor economically be provided by solar energy collection technology now or in the foreseeable future. Component redundancy will require up to three such nuclear power generation units to be in place at a lunar base. These are in the class known as SNAP (Space Nuclear Auxiliary Power) reactors – plutonium 239 or Uranium 235 powered with thermoelectric effect power conversion. The units envisioned for the expedition would be approximately the size of an office desk.

[20] The total cost of the expedition will not be exactly known until the final mass and volume engineering calculations can be completed and certain technology aspects developed but it will certainly be less than the $17B cost of the Lewis and Clark expedition.

Expedition Logistics:

For the sake of brevity the following discussion presumes familiarity with spaceflight principles and terminology. In order to accomplish the mission within a budget that can turn a profit a number of "tricks" must be employed. Before addressing each of these techniques in detail I will digress just a bit here to summarize how the mission might be carried out. In reading this, remember that we are building a business, not conducting a one-shot stunt. For this reason, the "system" must be designed to be completely re-useable (this is much easier to accomplish in LEO and on the moon that it has proven to be for earth-to-LEO transport). As will be seen, there will be high up-front costs to construct the system, whose capital assets will include a "barge" which shuttles between LEO and the lunar surface, and a mining/exploration outpost located on a permanently sunlit ridge near the south lunar pole[21]. But, just as with the construction of airplanes, that high initial construction cost can be amortized over many flights.

The concept herein described consists first of the construction of a lunar transfer vehicle (LTV, a.k.a. the "barge") in LEO. It will be fueled there and, following a single "burn" (engine firing), known as the TLI (trans-lunar injection) burn, will be placed into an escape velocity trajectory. Along the path to the moon (or, more precisely, where the moon will be when you arrive at that locus in cis-lunar space – since the moon is moving at roughly 1 km/s) mid-course corrections will take place (involving another engine burn). A third burn[22] will be required to enter into a circular, 100 km nominal altitude parking orbit from which the landing can be planned. A final sustained burn is required to de-orbit and land the craft. These maneuvers can be summarized as follows:

Trans-lunar injection from LEO	3.15 km/s
Mid-course correction	0.05 km/s
Lunar circularization at 100km	0.85 km/s
Lunar landing	1.63 km/s
Total:	5.68 km/s

The numbers at right are known as ΔV's (pronounced "delta Vees"), or velocity change increments. They are derived from considerations of orbital mechanics and will change only nominally for various lunar landing site scenarios and transit times from earth. At present, the only method for achieving these is through rocket propulsion. A simplified equation can be derived from Newton's second law that relates the mass of propellants required as follows,:

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[21] The reasons for this lay with the current hypothesis that chondritic meteorites, as well as comets, bearing frozen water have statistically impacted over the entire lunar surface over the last 4 billion years; only in the south polar region of the moon do craters exist in eternal shadow, where pulverized ice mixed with lunar soil might remain. In areas illuminated by sunlight such deposits would eventually sublimate into space.

[22] A 4th burn, known as a "plane change" burn, may be required to achieve the desired lunar polar trajectory, but the numbers presented above will be accurate within +/- 15%. Alternative low energy approaches to the plane change problem include layovers at the L1 Lagrange point, although plane change burns made from lunar orbit are not excessively costly and may lead to faster cycle time.

$$Q = M_{spacecraft+payload} \cdot \left(e^{\frac{\Delta V}{I_{sp} \cdot g_0}} - 1 \right)$$

Where:
Q = propellant mass, kg
M = vehicle mass (*unfueled*), kg
Isp = specific impulse (a measure of the effectiveness of fuels), seconds
g0 = gravitational acceleration constant (9.807 m/s^2)
e = constant = 2.718
ΔV = velocity change increment (m/s)

The intent of the above is not to overwhelm the reader with equations. Rather, it is to point out that the amount of propellant needed for the mission (which amounts to 80% of the mission mass budget) is related not only to the amount of ΔV needed, but also to the "dry" mass of the spacecraft and its non-structural cargo, as well as to the energetics of the propellant.

Why bother with all this? The reason is that the mission cost is directly controlled by the "mass budget" – the amount of "stuff" that has to go to the moon -- and the technology we use to get it there. We are paying for this by-the-kilogram. A significant reduction in the weight (mass) of the stuff taken will have a linear effect also on the propellant mass. It is for this reason that inordinate amounts of effort are spent on composites and other advanced methods of structural optimization in the aerospace industry. The energetics of the propellant, on the other hand, have an exponential effect on the amount of propellant required. At present, the best chemical mix that has been developed is liquid oxygen (LOX) and liquid hydrogen (LH2). Not coincidentally, this mix was used on the Apollo upper stage boosters as well as in the space shuttle main engines. Its use for lunar cycling missions is *unavoidable* at this time. Consequently, if a source for one or both could be found on the moon, it would dramatically change the logistics (and profit) situation.

Therefore, the primary activity once the lunar base has been established will be the search for, and production of, these propellants. Samples of lunar regolith (dust) from certain areas have shown high concentrations of the mineral ilmenite (iron titanium oxide), which contains approximately 40% by weight oxygen. The oxygen can be liberated using several techniques developed since Apollo. All of them require significant amounts of energy, hence the need for a robust, high power energy source at the lunar base. At this time two technologies are available which can meet these needs: solar and nuclear. The merits of these will be discussed further below.

The production of lunar oxygen is of key necessity to the maintenance of the lunar base, until such time as a fully closed ecological life support system (CELSS) can be implemented[23]. In gaseous form it will be used for metabolic oxygen makeup. In liquid form it can be used to

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[23] That is, life support based on the use of plant life to process carbon dioxide, generate replacement oxygen, and to provide food. Advanced work has been completed at a number of laboratories on this subject and it is considered a necessary component of any sustainable base on another planet.

extract carbon dioxide (through freezing and subsequent sublimation to vacuum) and to provide 80 percent of the mass of the propellants needed by the barge to return to LEO. Indeed, it is one of the bold premises of the plan described below that the initial flight to the moon from LEO will do so without the LOX necessary for the return mission. Although this will be done primarily for mission-enabling economy it will send a powerful message regarding our ability to really do things on the moon that have practical merit. Although not quite as drastic as Cortez burning his ships upon arrival in Mexico, it is equivalent to coasting there on trade winds without sails and expecting to build them from indigenous materials.

Perhaps the most intriguing reasons, economically and intellectually, for establishing a base on the moon deal with the potential for the existence of water – in the form of pulverized ice mixed with regolith – in deep south pole craters, specifically the Shackleton Crater and ones adjacent to it. The likelihood of its existence was demonstrated during a bi-static radar study conducted using the SDIO vehicle "Clementine I," which established a polar orbit about the moon in 1995. The results of this experiment point definitively to the presence of water in a 500 x 500-kilometer area centered about the south pole. Similar results were obtained from the Lunar Prospector small-sat mission.

Why is ice on the moon important? The primary reason is that it contains all the necessary constituents for high energy propellants (i.e. LOX and LH2, which can be created via electrolysis (and other methods) and subsequent liquefaction from water). It also has significant implications for sustained life support for LEO, lunar, and deep space manned missions. It is, pound for pound, more valuable in space than platinum at this time. Its implications to the profitability of the enterprise discussed herein are addressed below.

The plan, then, is to refuel the barge on the moon, at the very least using lunar derived LOX, and, if possible, lunar derived LH2[24]. The vehicle will then lift off to a direct lunar-escape/ earth-capture trajectory. As before there will be mid-course corrections. As the earth is approached, however, we have a different problem than faced when going to the moon. We have all that excess velocity that was originally necessary to leave the earth's gravity well, amounting to a significant 3.15 km/s. This energy has to be dissipated in any event to return to the earth. But we don't just want to return to the earth. We want to somehow end up in a parking orbit near our potential customer for the goods. As of this time, the most likely customer is going to be the international space station (ISS) and the industrial park that will eventually grow up in its vicinity. This facility will be placed in a 51° inclination, 400 km altitude orbit. "Inclination" refers to the tilt of the orbit relative to the equator, 90° being a true polar orbit, passing over both poles.

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[24] Yet another alternative, but less efficient, means for obtaining lunar-derived hydrogen is the extraction of Solar Wind hydrogen implanted in the lunar regolith (to a depth of around 3 m). Hydrogen as well as, importantly, trace amounts of implanted helium-3, can be obtained by sifting and heating substantial amounts of lunar soil. Helium-3 has been offered up by some ardent supporters as the prime enabler of a lunar economy, but this hypothesis rests on the development or production level fusion power reactors that utilize He-3 – He-3 fusion rather than the more traditionally investigated D-T (deuterium-tritium) reaction being investigated at Livermore and Los Alamos. In this proposal we take the more pragmatic view of building the LEO-moon economy first on the basis of fuel and life support trade. It is important to note that He-3 fusion power is a controversial subject in and of itself: high level professionals at Livermore emphatically dispute the utility of He-3 in fusion power production. For this reason, we list it here as an ancillary potential benefit should commercial value in this substance be proven at some time in the future; the near-term industrialization ROI case is the water/LH2/LOX economy.

To rendezvous with the ISS on a return from the moon one must first dissipate those 3 km/s, then maneuver to the ISS. The first operation can be done <u>without</u> propellant through a bold proposition known as "aerobraking." This has been done since the inception of the space program, but is known more commonly as "re-entry." The trick here is that we are not re-entering to the surface of the earth. Rather, we seek to dip into the atmosphere just long enough to dissipate those 3.15 km/s of excess velocity, whereupon the vehicle skips out the other side and back into orbit. It requires great precision and high speed active control of the vehicle. A graphic illustration of what such a maneuver might be like was depicted in the film "2010" by Arthur C. Clarke. Except in this case we are talking about doing it for real.

The aerobrake maneuver places the barge in an eccentric orbit, whose perigee (lowest altitude) coincides with the low point of the atmospheric pass and whose apogee (highest altitude, located 180° opposite around the earth) coincides with the ISS. Obviously, this requires precise timing and positioning, but is achievable with today's high speed onboard computers. At apogee the barge must fire its engines (the first time since the mid course correction burn) in order to boost the perigee to ISS altitude. From that point on only minor orbital maneuvering need be done to dock and/or park the barge in the vicinity of the ISS, completing the first cycle of the system.

The energy balance for the return trip looks something like this:

Trans-earth injection from lunar surface	2.37 km/s
Mid-course correction	0.05 km/s
Aerobrake (-3.15 km/s)	no propellant cost
ISS circularization burn	0.11 km/s
LEO maneuvering and docking	0.05 km/s
Total:	2.58 km/s

Notice the difference between this number and the amount of propellant related ΔV needed to go from LEO to the moon presented above.

At this point one needs to consider several scenarios, which affect the profitability of the company. What happens if you bring not only enough LOX back to sell (in order to make the mission profitable) but also to re-fuel the barge for another flight? What happens if you also bring back lunar derived LH2 to *completely* refuel the barge, so that no additional propellants ever need be brought up from earth? These two scenarios are investigated in the mass budget analyses presented below.

<u>A Review of the Novel Concepts of the Proposed Expedition:</u>

1) LEO Rendezvous:

The mass budget for the initial mission is approximately 200,000 kg in LEO. This could be transported to LEO either using the shuttle, shuttle-derived cargo rockets, or ELVs. Using the Russian Proton booster (See Appendix B) as the vehicle of economic choice for this task results in a requirement of approximately 10 launches[25]. Each flight will have to perform LEO rendezvous and docking at a location that can be used for mission staging. Fortunately, this procedure has been immensely simplified through the advent of phase differential real-time GPS positioning (accurate to less than a centimeter at 20 Hz update rates) and high precision laser radar. Using rather simple, re-useable, smart cargo capsules, the arrival and storage of the vehicle components can be automated.

So, where do you do this assembly? The logical location is the International Space Station (ISS) since it makes use of existing national assets which are currently under-utilized. With presidential direction, the use of the ISS, the shuttle fleet, and the existing shuttle astronaut corps to perform the staging for the expedition makes good sense. Although this may not be the most economical solution for this stage it has the political benefit of providing NASA with a specific, focused mission that is well within its purview to carry out.

2) Inflatable Spacecraft: Crew Quarters & Liquid Storage Facilities:

Mass reduction is the key to profitability on the first mission. In order to allow the use of small launchers, and to minimize bolt-up operations on orbit, human habitation quarters must be dealt with in a different fashion than heretofore attempted. We are proposing to use inflatable habitation modules. This has been investigated in the past by several groups, notably Martin Marietta in relation to the conversion of the shuttle external tank to an LEO industrial lab, and by Lowell Wood and associates at Lawrence Livermore as a potential Mars mission solution. Both ideas were rejected by the establishment as “too radical.” For our approach they will be enabling. The basic system would consist of a dual-hull design, inflated using pressurized urethane, which ultimately achieves a rigid set capable of sustaining structural loads. External debris cladding will be added for stays in LEO. These habitation modules will be among the first payloads to orbit during the construction phase, and it is from these that the assembly crew will work, with the ISS serving as a "safe haven" backup. Identical systems will be used to establish the lunar habitat complex.[26]

3) Redundancy, Commonality, and Simplicity:

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[25] As will later be shown, nearly 80% of the LEO mass budget comes from propellant. The provision of such propellants from the moon, and the fact that the vehicle is being designed to be re-useable, means that subsequent re-supply from earth would only require one or two small launches in the worst case scenario and none in the best.

[26] In the late 1990s NASA funded, then cancelled a program called “TransHAB” and “BioPlex” at JSC in Houston. They first built a prototype ½ scale model of an inflatable add-on module to the ISS that would be a stand-in for an inflatable Mars transfer vehicle for humans. The BioPlex side investigated using plant life for closed-cycle life support, in experiments much more controlled than the controversial “BioSpere” experiments of the early 1990s. Both programs did good work but were too radical for NASA. They were cancelled to make more funds available for the ISS which was generating substantial cost over-runs. It is our intention here to take what they learned and move on to practical implementation at full scale; NASA could tasked with completing this important work for the expedition.

It is intended that, in order to secure the maximum likelihood for expedition success, that multiple, independent transfer vehicles will be created, each staffed by a third of the final crew. Each craft would be identical to the next and capable of transporting the entire crew if required. Since each craft would be identical, they could be cannibalized for spare parts on the moon if required for maintenance to insure safe return of the crew in the event of mechanical malfunction or accident on landing or takeoff from the moon. The over-arching design rules will be of simplicity, parts commonality, and the ability to conduct field repairs and component swap-outs. A direct benefit of this approach will be the ability to reap economies of scale in manufacturing. Furthermore, by designing simple systems that are inherently fault-tolerant and field-repairable one can avoid the tedious, expensive, and time consuming issues of "space qualifying" each and every system that will fly. Unlike complex Earth-to-LEO launch systems, it is in fact very feasible to achieve the above objectives – they are not mutually exclusive – for LEO-Lunar transfer vehicles as well as for lunar habitation. The vast majority of the components and subsystems needed are available off-the-shelf with proven reliability. This statement could not have been made 20 years ago.

4) High Density Power Systems:

Current estimates place lunar base power needs at approximately 50 to 75 kW. The majority of this is devoted to a) lunar oxygen processing and b) CELLS operation, which requires tuned wavelength light sources to grow sustainable hydroponic plant culture, which would ultimately supplant physio-chemical life support processes (oxygen makeup and CO2 absorption) as well as water recycling and food. The provision of 75 kW of electrical power in space is no trivial matter. Yes, solar power is there – at continuous incident power levels of 2 kW per square meter. But it is not free. Using the best available technology (galium-arsenide photoelectric concentrators) one watt (1W) of space-rated power can be had for approximately $1000. For 75 kW that amounts to $75M and is subject to decay (about a ten year maximum lifetime with declining output every year). Certain crater rims near the south lunar pole do have permanent solar illumination (and are not subject to the 2-week lunar night). This would limit the choice of lunar base location. The second alternative power source is a space-rated fission/thermionic conversion (SNAP). The Russians produced such a reactor known as Topaz II[27]. This system uses U235 isotope to generate heat, which is directly converted to electricity by the thermoelectric effect. The unit runs for 100 years. One unit would meet our mission needs and would cost approximately 1/100th that of solar power (amortized over a 100 year lifetime).

5) Creation of return propellants on the Moon:

As described above, the mission depends upon being able to manufacture LOX on the moon. At present, several companies (notably the Japanese) have been working on self-contained devices Such power levels will be crucial for processing ilmenite into gaseous oxygen. An interesting, and possibly useful by product, is raw aluminum and titanium, which might one day be converted into viable structural elements. Although several fully re-cyclable processors have been designed, using hydrogen and carbon as catalysts, all processes require fairly high electrical

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[27] Topaz II was evaluated at Los Alamos lab and it was believed that better systems could be developed within the U.S. Funding for a next-generation Space Nuclear Auxiliary Power (SNAP) system has been proposed by NASA as part of the Prometheus Program in collaboration with DOE. The expedition will be crucially dependent upon the success of this research program and it should be strongly supported by Congress. A more complete discussion of the present state of SNAP technology is presented in Appendix E.

currents, hence the need for the types and levels of power described above. The gaseous oxygen can be liquefied using off-shelf liquefaction systems and subsequently stored in regeneratively cooled dewers. It will be one of the project's primary technical concerns to develop large capacity inflatable dewars, capable of holding several score tons of LOX, both for long term storage on the moon, as well as for attachment to the barge for transport to LEO. Owing to the mission criticality of LOX production, fault tolerant and redundant system implementations will be used (i.e. there will be at least three independent means for LOX production on the moon with the ability to self-diagnose and allow repair in-situ).

6) One-pass Aerobraking for Earth Return and LEO Rendezvous:

A useful analogy concerning the earth's atmosphere was presented during the movie **Apollo 13**. It was explained that if the earth were the size of a basketball, the moon would be the size of a grapefruit some 5 meters away, and the earth's atmosphere would be, relatively, about as thick as a sheet of paper. The trick with aerobraking, particularly the "dip and skip" variety intended to be used, is to precisely hit that "paper thin sheet" at the correct altitude, latitude, longitude and orbital inclination, and at the proper time. The intent is to insure that a) the barge does not permanently skip off into space; b) it does not completely re-enter (and burn up); and c) the above parameters are hit with sufficient precision to bring the barge out of the maneuver with the the same orbital parameters as the ISS and be within maneuvering range when it gets there. Despite the seeming complexity presented above, there are several things in our favor that were not available, for example, on the Apollo shots. The most important of these is the ubiquity of high speed, interactive computer graphics and computational engines. A desktop Pentium-4 or low end Silicon Graphics computer today has more computing power in one place than all of Mission Control had during the Apollo missions. These are sufficiently lightweight, low power, and low cost that multiply-redundant *onboard* mission control systems can be implemented on the barge itself. Besides the off-shelf availability of highly precise, low cost inertial measurement units (IMU's) and the ability of the Deep Space Network (DSN) to precisely uplink vehicle position, final approach to the aerobraking maneuver will be GPS controlled to centimeter level precision in real-time.

In reality, the earth's atmosphere is not uniform. It actually is a concentric shell approximately 70 kilometers thick through which the density increases from vacuum to sea level conditions. The aerobraking barge can be considered as a bullet shot through this spherical shell of gas, the density first increasing until the closest point of approach to earth, then decreasing out the other side. Below 40 km altitude it will actually be possible to create lift and thus to steer the vehicle as needed to dissipate the velocity precisely.

Aerobrakes have been researched extensively at NASA. One crucial detail to be studied in preparation for the expedition will be the ability to design an aerobrake (possibly a deployable system) that involves actively controlled, ultra-high surface-to-mass ratio systems. Such an approach will lead to reduced thermal loading with the objective of never exceeding the ionization threshold. This would, in turn, permit unbroken radio contact with both the redundant ground control station as well as with the GPS reference satellites for trajectory and attitude control.

7) LOX to LEO for Subsequent Missions:

It will be essential for enabling a positive return on investment for the barge to "use its own gas" to get back to the moon on subsequent trips. Thus, the barge has to be designed for several criteria:

- It has to be able to initially establish the lunar base and guarantee sufficient onboard propellants to permit an abort to LEO should something go wrong.
- It must carry enough LOX (at least) back to LEO to conduct the next outbound leg to the moon.
- It must carry enough excess LOX to sell for profit in LEO.

Without such capability there is no hope of making the system profitable. As will be seen, it is necessary, but not necessarily sufficient, to guarantee profitability.

8) The Ice Factor:

The issue of potential ice deposits at the South Pole (Shackleton Crater) region of the moon was discussed above. At this time, its discovery is more important for its implications to barge transit profitability than it is for life support reasons, since LOX (derived from regolith) can be produced anywhere on the moon and can be used to guarantee lunar base sustainability. If lunar LH2 can be produced, then several things happen. First, no LH2 need be taken to the moon in order to provide the fuel (as opposed to oxidizer) for the return trip. Since the propellant represents nearly 80% of the mass budget, this is a tremendous boon if it can be had on the moon. Secondly, the ability to return LH2 and LOX to LEO, at the very least in the amounts needed to fuel the return trip of the barge to the moon, will reduce the dependence on earth-to-LEO boosters to the absolute minimum (largely then only high-tech instruments and computers, special foodstuffs, special purpose hardware, and personnel changeouts). The effect this has on overall mission cost and profit is discussed further below.

9) Crew Return to Earth & Restaffing:

At some point personnel (presently estimated at 12 to 18 for the initial expedition) will need to be rotated, if this is to be a continuing endeavor. We believe the first mission, because of the unknowns on the moon, and because substantial prospecting may be involved in the search for ice, as well as the establishment, test and operation of man-tended processing machinery, will represent roughly a one to two year duration on the surface of the moon. Later missions can occur at a much more frequent rate, largely controlled by the industrial infrastructure and the ability to remotely operate LOX and LH2 production.

Because the "barge" is intended to remain either on the moon or in LEO, we need an economical means to get personnel to and from the LEO staging point for the barge. This could be via the space shuttle, Russian soyuz craft, or via ultralight RVs that take advantage of the high surface-to-mass aerobrake technology discussed earlier. This latter subject has been addressed previously by the author in a white paper entitled "Project SpaceDiver" as a low-cost alternative escape craft for the ISS.

In the calculations presented below we assume no breakthroughs in propulsion technology over the next decade and that expendable launch vehicles (ELVs) will remain the only available mechanism for transport of equipment to LEO. At any time, however, this situation could change if upstart companies begin to succeed in their present nascent attempts at addressing the space tourism arena. But these would not change the logistics nor the profitability of the LEO-lunar commerce chain described in this paper. They would, however, provide more demand for the products to be offered from the LEO-lunar trade pipeline and hence fuel expansion of lunar facilities and transfer craft since, naturally, tourism demand would extend to the moon once proven feasible. We thus see this as the paradigm for the near (30 year) future: lower (but not ultra cheap) cost boost from earth to LEO combined with high surface-to-mass re-entry through the use of a space-diver like vehicle or via commercial craft once the tourism vehicles succeed in reaching LEO.[28]

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[28] Present contenders for the "X-Prize" are only shooting for 100 km elevation in a sub-orbital shot, but several are believed to be within striking distance of that objective in the 2004 time frame.

Commercial Opportunities:

The real question is: what can we bring back of value from the moon? We have already addressed the value of lunar LOX and LH2 to reducing costs of operating the barge. But "selling to ourselves" does not make money initially (but see below). Who else needs propellants and water in LEO? First, the ISS is a reality, and it has specific yearly needs for both water, LH2, and LOX. The latter two are needed because, even at 400 km altitude, there remains a tenuous atmosphere. This atmosphere, however slight, produces drag that slowly, over months time, reduces the altitude of the ISS thereby further increasing aerodynamic drag as the atmosphere thickens at lower altitudes. Periodic “reboost” of the ISS is therefore required, and to do this you need propellants. The exact amounts that the ISS could be counted on to purchase have not yet been established, but the need for these propellants, and water, in LEO will steadily increase as economical access to space becomes more available.

The availability of cheap (relative to earth-to-LEO supplied) lunar derived propellants in LEO will change the way spacecraft designers think, almost immediately, for any vehicle intended for GEO and beyond. It will also be needed for any OTV (orbital transfer vehicle) that would be developed for servicing both high LEO and GEO satellite assets. These two factors spell a dramatic change in the design and servicing of national security assets in orbit that could serve to not only improve the quality and utility of those assets but to dramatically reduce both their design, development, manufacturing, and critically, operating costs. The ability to routinely service these assets cannot be understated. Neither can the cost benefits obtained by eliminating the requirement to transport from Earth to LEO the propellants needed to boost those assets to their ultimate orbital destination.

There is also another potential profit avenue that does take advantage of “selling propellant to ourselves,” and that is lunar transport of people. At first, these would most likely be government funded scientists desiring to conduct experiments on the moon. It has long been recognized that that radio and optical telescopes placed on the “dark side” of the moon (that which permanently faces away from the earth) would dramatically extend our vision beyond that of even the LEO based Hubble telescope. However, in the long run “high adventure” tourism, catering at first to the exceptionally rich, may permit such a business to be self-sustaining and expand, gradually making the experience available to greater and greater numbers.

As mentioned in footnote 23 above, there is also the potential for extraction of helium-3 from lunar regolith (the helium-3 comes from implantation of highly energetic solar wind particles). This material, in quantity, has enabling characteristics for practical fusion power on earth since initiation and maintenance of the fusion power cycle is immeasurably easier with He-3 – He-3 reactions than with classical deuterium-tritium (DT) reactions. A few ardent space scientists have ventured that this commodity alone will propel and Earth-Moon economy, but for the present scenario we view it as a side benefit and work the numbers purely based on what we are relatively certain to find in abundance that is straight-forward to process on the moon and to return to LEO.

In the remainder of this paper I will focus only on estimating what it would cost to conduct the initial lunar base establishment mission and to presume that we can ultimately find a buyer for as much LOX, LH2, and water that we can mine and transport to LEO. Other potential profit making uses of the system, once established and the first mission flown, can be investigated later.

Preliminary Costing Exercise:

Establishing a budget for a lunar mission is much like estimating how much it will cost to truck some heavy item from one side of the U.S. to another. Usually teamsters charge by the kilogram. Internally, they must consider the acquisition, maintenance, and overhead (including salaries) costs associated with the truck and then add some markup to make a profit. The particular exception we must deal with is that our business is actually a two-stage system. We are not really going from point A to point B on the opposite side of the country. Rather, we are going from point C, about halfway between points A and B, to point B. And we cannot go out to the local space truck dealer in LEO and buy a truck. We have to build the truck at point C and we have to pay exorbitant rates (per kilogram) to get the parts we need sent there to build the truck. And the heavier our truck, the more it costs us, in terms of fuel, to go between points C and B. So, we need to figure out what everything weighs (its mass, in kilograms) and minimize waste.

The above is a rough analogy of the exercise necessary to plan a lunar base. You start with a "mass budget," then figure out what it takes in terms of fuel to get you where you want to go. We have, of course, a few unusual pieces of required hardware that need to go to our outpost. In the nine spreadsheet tables presented at the conclusion of this paper (labeled Studies 1 through 9) I have made some considered estimates of the mass and propellant budget needed to conduct the mission. The hardware has been separated into mission specific subheadings, including

- Orbit transfer/landing vehicle (i.e. the "barge")
- Lunar surface hardware (i.e. the outpost)
- Lunar surface consumables (i.e. what the people working there need to survive)
- Personnel (the mass of the crew and their personal belongings)
- Propellant mass budget

The nine studies deal with the following scenarios:

Table 1: Overall Mission Cost Summary

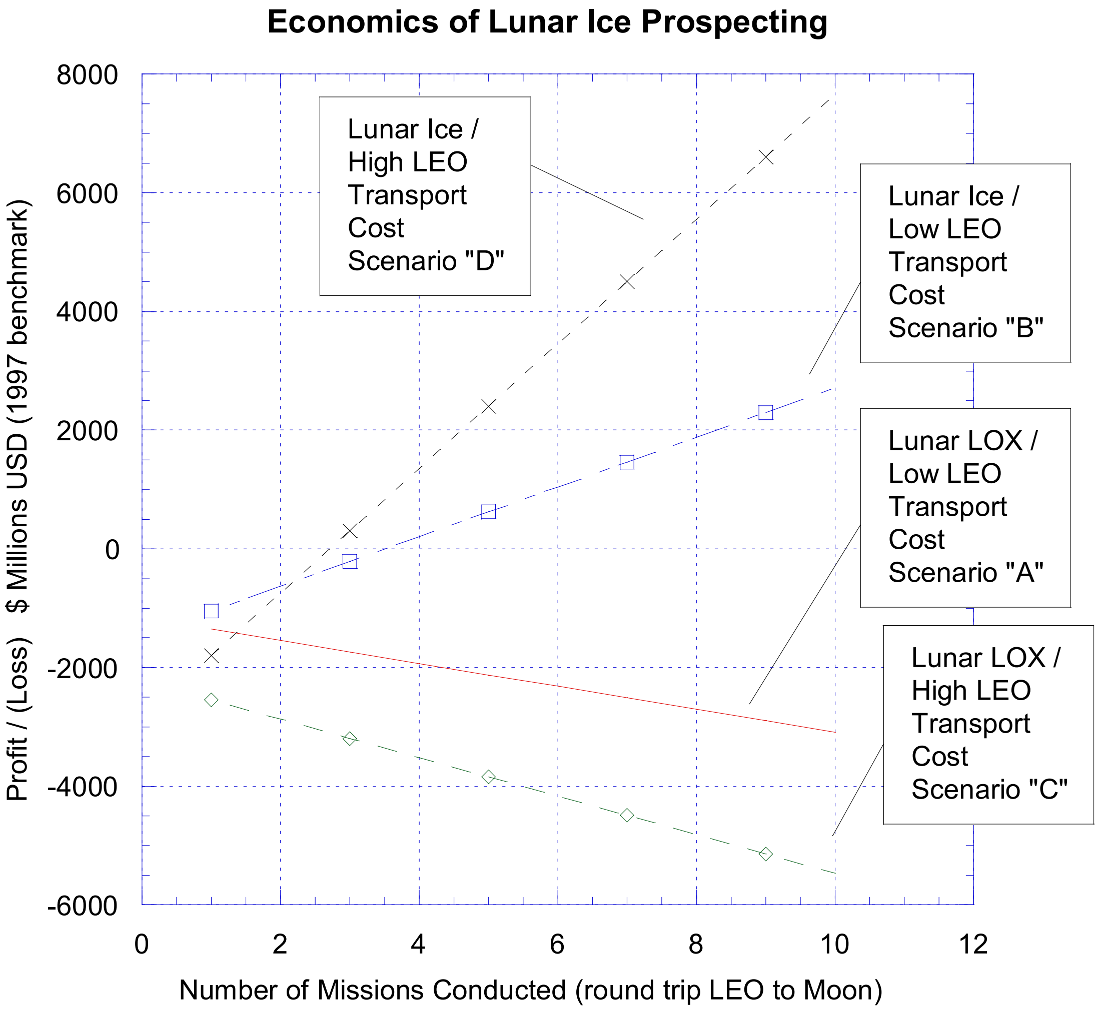
STUDY	**Mission**	**Special Variables**	**Cost of 1st Trip ($M)**	**Cost of 2nd Trip ($)**
1	LEO to Lunar Base	First Mission $6600/kg to LEO from Earth LH2 supply brought from Earth Lunar Base Hardware included	2861	N/A
2	LEO to Lunar Base	First Mission $3300/kg to LEO from Earth LH2 supply brought from Earth Lunar Base Hardware included	1479	N/A
7	LEO to Lunar Base	First Mission $6600/kg to LEO from Earth Lunar-derived return LH2 Lunar Base Hardware included	1160	N/A
8	LEO to Lunar Base	First Mission $3300/kg to LEO from Earth Lunar-derived return LH2 Lunar Base Hardware included	629	N/A
3	LEO to Lunar Base	Second Mission $6600/kg to LEO from Earth LH2 supply brought from Earth	N/A	638
4	LEO to Lunar Base	Second Mission $6600/kg to LEO from Earth Lunar-derived return LH2	N/A	11
5	LEO to Lunar Base	Second Mission $3300/kg to LEO from Earth LH2 supply brought from Earth	N/A	319
6	LEO to Lunar Base	Second Mission $3300/kg to LEO from Earth Lunar-derived return LH2	N/A	6
9	Lunar Base to LEO	All Missions (prepaid as part of the "up" budget)	N/A	N/A

Studies 1,2, 7, and 8 deal with the cost of establishing the lunar base. As can be seen these range from $1479M to $2861M (Studies 2 and 1, respectively) for the ambitious (but not bold) scenario where the crew does <u>not</u> take any oxidizer to the moon for the return flight. This is a fairly conservative assumption, given the known oxygen content in lunar regolith, and the fact that proven technology to extract and liquefy that oxygen will be taken along. The bold scenarios (Studies 7 and 8) take the next step and presume that lunar ice will be discovered. The amount needed is surprisingly small. Simply back convert from the numbers listed in the tables for the mass of LH2 needed and consider that 1 kilogram (i.e. one liter) of water contains 110 grams of hydrogen. From this, it is relatively straight forward to extract and produce LH2. **If it exists**. This question has tentatively been answered by the Clementine I and Lunar Prospector missions and the answer appears to be "yes," but the exact position of specific deposits (down to, for example, a 100 m area) have not yet been determined. As previously mentioned, robotic precursor missions should be launched to narrow down the location of potential ice deposits in preparation for the human prospecting and exploitation expedition.

The reason for all the interest in lunar ice is evident in the change it implies to the first mission cost: $1160 and $629M, respectively, depending on high or "low" launch costs from earth to LEO. That cost reduction carries over into the subsequent mission costs described in Studies 3 to 6. On all following missions we are able to ditch the mass of the habitat and a few other pieces of infrastructure that only need be brought to the moon once. The overall costs depicted in Table 1 assume the sale of 230,000 kg of LOX in LEO on the return of each mission, at a price at least $1100/kg less than the "going rate" for the scenario considered. Such a discount will make it untenable for anyone working in LEO and to those launching missions beyond LEO to not make use of that asset. Profit or Loss indicated in the Study spreadsheets assumes this sale to take place. Table 2 shows what happens if we propagate these initial capitalization costs and individual mission profits/losses for ten missions. On a realistic basis, it could be expected that several missions a year could be run once the base, mine, and liquefaction facilities are fully operational. Figure 1 also shows the same information graphically.

Table 2: Cumulative Profit for Various Mission Parameters

Mission Number	Lunar LOX Low LEO Transport Costs Plot "A"	Lunar Ice Low LEO Transport Costs Plot "B"	Lunar LOX High LEO Transport Costs Plot "C"	Lunar Ice High LEO Transport Costs Plot "D"
1	$ (1,354.00)	$(1,054.00)	$ (2,547.00)	$ (1,799.00)
2	$ (1,547.00)	$ (635.00)	$ (2,871.00)	$ (749.00)
3	$ (1,740.00)	$ (216.00)	$ (3,195.00)	$ 301.00
4	$ (1,933.00)	$ 203.00	$ (3,519.00)	$ 1,351.00
5	$ (2,126.00)	$ 622.00	$ (3,843.00)	$ 2,401.00
6	$ (2,319.00)	$ 1,041.00	$ (4,167.00)	$ 3,451.00
7	$ (2,512.00)	$ 1,460.00	$ (4,491.00)	$ 4,501.00
8	$ (2,705.00)	$ 1,879.00	$ (4,815.00)	$ 5,551.00
9	$ (2,898.00)	$ 2,298.00	$ (5,139.00)	$ 6,601.00
10	$ (3,091.00)	$ 2,717.00	$ (5,463.00)	$ 7,651.00


Economics of Lunar Ice Prospecting
Profit / (Loss) $ Millions USD (1997 benchmark)
8000
6000
4000
2000
0
-2000
-4000
-6000
0
2
4
6
8
10
12
Number of Missions Conducted (round trip LEO to Moon)
Lunar Ice / High LEO Transport Cost Scenario "D"
Lunar Ice / Low LEO Transport Cost Scenario "B"
Lunar LOX / Low LEO Transport Cost Scenario "A"
Lunar LOX / High LEO Transport Cost Scenario "C"

Conclusions:

The principal goal of the proposed federally funded expedition is to demonstrate to the private sector that there is a business case for establishing an LEO-moon trade route, in effect, that there is a positive ROI. The above analyses indicate, clearly, that substantial profits can be made from this endeavor, despite serious up-front capitalization costs. Ironically, the best profit rate is made if the current launch systems for earth to LEO transport maintain the status quo, and thus increase the value of goods brought from the moon. Short of a major physics breakthrough this status quo can be anticipated to exist for the next 50 to 100 years. But to take advantage of this, the up-front costs to establish the business are commensurately higher.

Lunar LOX alone will not enable a profit to be made. It is the hydrogen component of water ice (or solid NH_3) that changes the entire scenario – by breaking the costly tie to earth based transport for fuel for the barge (remembering that 80% the cost of a mission lies in propellant mass). It is therefore critically important that the first mission find viable deposits of ice at the south lunar pole and exploit them. There are several ways to view this problem/opportunity. The first is to believe the Clementine, terrestrial bistatic radar, and Lunar Prospector imaging spectrometer data and plan the mission on the basis that somewhere in the 30 km diameter area of total darkness inside Shackleton Crater lies the ice and that it is only a matter of going there and seeking it out. This is, in the author's opinion, no great task for a seasoned expeditionary team that has the mind set to establish a base there for a year or more with the mission of finding the ice. The backup plan would be to develop more time-consuming systems (from the standpoint of time required to process sufficient lunar H2) that separate implanted solar wind hydrogen from the lunar regolith. The presence of implanted H2 in lunar regolith has been verified through analysis of Apollo samples, so its presence is not in doubt. However, in the analyses presented below we have not considered the mass of such backup lunar H2 generation machinery; this would be an alternative to be considered following acceptance of the expedition concept, just as trade studies would also need to be conducted on various habitation and power generation technologies in addition to launch manifesting and staging options. The most effective means of resolving the above issues would be to conduct a series of robotic precursor missions to narrow the location of the ice deposits in preparation for the human expedition.

The results presented herein are, as of this draft, the work of a single individual and as with all individual endeavors there is the potential for oversight and error. However, the author does believe things to be approximately correct and furthermore that the conclusions drawn above will still hold up under more rigorous analysis. The author makes this statement with the background of having planned and executed 45 terrestrial exploration expeditions (comprising more than six years in the field cumulatively), many of them involving advanced technology in remote, hazardous locations with teams as large as 150 individuals from a dozen nations for periods of up to 4-1/2 months on site as well as having worked professionally for 23 years on spacecraft related issues, life support, 3D sensing, and robotics and autonomous machinery design[29]. Places where errors will be highest will involve hardware development and procurement, where some things may have been completely overlooked. The hardware budgeting was done en-masse on the basis of it costing $1000 per kilogram. This has proven to be a useful rule of thumb for high-tech goods, but it may totally miss the mark for some highly specialized gear: RL-10 engines,

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[29] Full resume is appended

oxygen reducers and liquifiers, the development of inflatable cryogen storage systems, and the acquisition and orbital insertion of SNAP reactors are things that come immediately to mind.

For those with the authority within the United States government to enable this expedition I would recommend the following steps be taken at this time:

Establish and fund a Presidentially-appointed Joint Lunar Expeditionary Program Office to lead the expedition with the designated expedition leader as the head of the office reporting directly to the President. This office should be empowered by Presidential mandate with the mission of achieving the objectives set forth herein within five calendar years and, by express Presidential order, have the direct support of agencies and departments that report to the President. Initially this office should be charged with answering the five questions posed by the expedition:

1) Are there any engineering show-stoppers? Specific tasks would include: completion of a more detailed first-order engineering review to insure that no gross errors in technology or hardware costing have been made and that what is being proposed is within the realm of technical feasibility within five years. Directly address, through a series of sub-studies, a list of technological topics that require further engineering design and assessment. Among the controversial topics will certainly be the ability to design and construct the expedition's SNAP reactors in a reasonable time period and within reasonable budget; detailed CFD analyses of candidate lunar return aerobraking architectures (and their hypersonic heating loads, stability, and control options) need to be conducted to verify this portion of the mission profile; the capability for long term cryogen storage in inflatable systems requires detailed investigation, as does the development of automated mechanisms and sensors for proximal detection of hydrogen while on the lunar surface and the processing of lunar regolith to harvest it. Studies of many of these topics are either underway currently (e.g. through NASA) and/or have been reviewed in the past. This stage of the effort will involve both original calculations where required as well as culling key information from extant sources on related technology.

2) Is the budget realistic?; Specific tasks would include: performance of a detailed economic analysis of the plan as laid out here and to elaborate it in greater specificity. Draw up a list of budgetary and legal issues that would need to be resolved in order to enable the expedition. Most crucial to this team's success will be guidance from the White House on what is and what is not feasible in terms of budget and timeline. Included in this discussion will be the explicit elaboration, by White House staff (OSTP, OMB), of how the expedition will be sold to Congress.

3) How would legal issues be dealt with (e.g. bypassing tariffs on the use of foreign boosters etc.)?; Again, this is an area where existing White House staff (OSTP, OMB) and related departments (e.g. DOC, DOT, FAA) will have useful input. However, the White House should be clear to reign in such discussion so as to make it proactively enable the expedition, not preclude it.

4) What is the best fiscal-institutional structure for the expedition? We state clearly above that the initial act to enabling the expedition should be the formation of a Joint Lunar Expeditionary Program Office that reports directly to the President. Other organizational concepts are possible (e.g. federal space corporation; non-profit corporation; military

expedition; special project under an existing federal entity etc.). The White House should decide upon the most propitious organizational form to enhance the success of the expedition and to avoid political roadblocks within the government by those who might oppose the undertaking.

5) <u>What should be the makeup and nature of the crew</u> needed to carry out the expedition and under what management structure should it function? Analyze the mission requirements and define the nature of the crew that would be needed to carry out the expedition. Establish a tentative desired skills mix and crew size and the types of prior expeditionary experience that would be considered crucial for them to be stable, level-headed producers on a two year mission. With regard to this latter element it is important to recognize that NASA has no field expertise in the domain of long duration expeditions. Although it will be useful to have certain of the psychologists associated with the astronaut selection office, a selection of the ISS and MIR astronauts, and the input of those Apollo astronauts who landed on the moon be involved at this stage, it will in fact prove more useful here to have expeditionary leaders (both military and civilian) of long repute offer their advice – people who have worked in tough environments for months to years – on how to select in and select out potential crew members. Included in these discussions will be the issue of authority structure and the maintenance of discipline on a mission where, unlike Lewis and Clark, no crew member can be dismissed once the expedition leaves LEO. This process would be led by the expedition leader designate who shall, by Presidential authority, have final and full authority to select and assemble, as well as to dismiss, the expeditionary team.

All groups involved in the above studies should be carefully selected from no-nonsense talented engineers, financial managers, legal staff, and seasoned expeditionary leaders who are proven producers. Although individuals from established aerospace corporations and potentially individual NASA scientists and/or engineers may be invited, the commission should be controlled under the utmost secrecy until the President makes an announcement regarding the intent to launch the mission. Very specific objectives for each group will need to be laid out such that by the end we can fuse the findings and have a clear determination as to:

- The engineering feasibility of the mission; specific technology needed to carry out the expedition; and a clear path to assembling, testing, and fielding the necessary hardware.
- A refined budget estimate and an assessment of the financial feasibility of the venture for producing a positive return on investment over time.
- A plan for dealing with the legal issues presented by the alternative methods posed by the expedition plan.
- A plan for final organization and management of the expedition from inception through transferal to industry upon successful completion of the mission.
- The optimal size, makeup, and character of the crew and a plan for recruitment.

The Joint Lunar Expeditionary Program Office would then be charged with presenting the above findings along with a recommended plan to the President for making the Shackleton Crater Expedition an Executive Initiative within the Bush presidency.

APPENDIX A: Mass and Financial Budget Sheets

Peary Crater Expedition Lunar LOX/Ice Reconnaissance/Recovery Mission

September 2003 Bill Stone

Lunar Landing Mass Budget: First Mission
STUDY 1: OPTIMISTIC TRANSPORT COST TO LEO
Note: return LH2 brought from earth

Orbit Transfer/Landing Vehicle

	Dry Mass Estimate (kilograms)	Notes:	Precision 1=Good 5=WAG
Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
LH2 for Earth Return	44790	Brought from earth for return	
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Lunar Surface Hardware

Inflatable Surface Habitat (cap. 6, quad-cell; 4m dia x 12 m long)	302	Matl: 2 kg/m^2	2
Inflatable Surface Habitat (cap. 6, quad-cell; 4m dia x 12 m long)	302	Backup unit	2
Primary habitat airlocks (5 at 50 kg each)	250	dual egress ports plus one central isolator	2
Secondary habitat airlocks (5 at 50 kg each)	250	dual egress ports plus one central isolator	2

Airlock gas recycle pumps, primary habitat (2@50kg)	100	recovery of airlock gas prior to egress	4
Airlock gas recycle pumps, secondary habitat (2@50kg)	100	recovery of airlock gas prior to egress	4
Initial Habitat Atmosphere (N2, O2) Prime Habitat	129	Air at 1 bar = .96 kg/m^3	1
Initial Habitat Atmosphere (N2, O2) Backup Habitat	129	Air at 1 bar = .96 kg/m^3	1
Cabin leakage make-up atmosphere (prime habitat)	250		4
Cabin leakage make-up atmosphere (backup habitat)	250		4
Cabin furnishings (sleep, cook, meeting, work, bathroom areas)	500	prime habitat (also includes laundry & shower)	4
Cabin furnishings (sleep, cook, meeting, work, bathroom areas)	500	backup habitat (also includes laundry & shower)	4
Workstations/Communcations/Local Mission Control	250	Full mission control capability onboard	
Fission-Thermionic Reactor, 100 kw (main power)	2500	Topaz class (russian launched to LEO)	2
Emergency Sustaining Solar Cell Panel Power System (2kw)	250	GaAs Focused 20% efficiency array	4
Gaseous O2/H2 Fuel Cell Storage System (Emergency Storage)	500	14-day at 5% power	4
LOX Generation plant (prime, high production rate)	2000	ilmenite (reduction) reduction	5
LOX Generation plant (backup, low production rate)	500		5
LOX Storage System (lunar product) & refridgeration	1000		4
Cryogenic CO2 processor	100		
4 EVA suits plus repair parts/materials	300		2
Ice bulk melter & bio filter	300	small demo system in case ice is found	3
Water storage tank	100	fuel cell product storage + excess for ice	3
Water cracking unit (gaseous O2/H2 production)	100	for fuel cell power	5
Utility truck	1500	NMH-electric, 600 km range, 4 ton capacity	5
Hydroponics facility	600	capable of sustaining 6 individuals indefinitely	4

Lunar Surface Consumables (non-regenerative)

6-months reserve FD food	500	use microwave for cooking; 300 g/day/person	2
6-months reserve water (assuming 80% physio-chemical recycle)	1728		3
Non-recyclable personal consumables	540	personal toiletries etc.	3
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Cabin ECLSS system hardware	100		3
General repair kit	100	patch kit, lights, duct tape, tool kit etc.	
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3

Personnel

3 persons @ 100 kg max	300		1
personal clothing @ 30 kg/person x 3 persons	90		2
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms) (including propellant)	72750	Spacecraft "Dry" mass + payload

Propellant Mass Budget

LOX (oxidizer)	**220927**	Earth-to-Moon plus abort reserve	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**55217**	Round trip	2
Total Propellant Budget:	276144		

Total Spacecraft Mass (fully loaded with fuel & oxidizer)	348894
Propellant Mass Fraction	0.79

Transportation Cost (earth to LEO staging)	$ 1,151,351,685	$6600 per kilogram to LEO (500 km, 51-deg)	
Hardware Cost (purchase price)	$ 41,940,000	$1500 per kilogram for hi-tech hardware	
Engineering & Test	$ 40,000,000		
Total: Project Development & Conduct:	$ 1,233,291,685		
Contingency (10%)	$ 123,329,169		
Profit (10%)	$ 123,329,169		
Total Project Budget	$ 1,479,950,022	To establish permanent lunar base and allow	
		for return to LEO.	
Sale of Lunar LOX (returned from moon)	$ 125,732,200	Based on assumption of NO lunar ice	
Sale of Lunar LOX (returned from moon)	$ 424,974,000	Based on assumption of DISCOVERY of lunar ice	
Profit (if NO lunar ice available)	$ (1,354,217,822)	at end of one-cycle	
Profit (if lunar ice IS available)	$ (1,054,976,022)	at end of one-cycle	

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Lunar Landing Mass Budget: First Mission
STUDY 2: CONSERVATIVE TRANSPORT COSTS TO LEO
Note: LH2 return supply brought from earth

Orbit Transfer/Landing Vehicle

	Dry Mass Estimate (kilograms)	Notes:	Precision 1=Good 5=WAG
Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
LH2 for Earth Return	**44790**	In this scenario, LH2 must be brought from earth	2
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Lunar Surface Hardware

Inflatable Surface Habitat (cap. 6, quad-cell; 4m dia x 12 m long)	302	Matl: 2 kg/m^2	2
Inflatable Surface Habitat (cap. 6, quad-cell; 4m dia x 12 m long)	302	Backup unit	2
Primary habitat airlocks (5 at 50 kg each)	250	dual egress ports plus one central isolator	2
Secondary habitat airlocks (5 at 50 kg each)	250	dual egress ports plus one central isolator	2

Airlock gas recycle pumps, primary habitat (2@50kg)	100	recovery of airlock gas prior to egress	4
Airlock gas recycle pumps, secondary habitat (2@50kg)	100	recovery of airlock gas prior to egress	4
Initial Habitat Atmosphere (N2, O2) Prime Habitat	129	Air at 1 bar = .96 kg/m^3	1
Initial Habitat Atmosphere (N2, O2) Backup Habitat	129	Air at 1 bar = .96 kg/m^3	1
Cabin leakage make-up atmosphere (prime habitat)	250		4
Cabin leakage make-up atmosphere (backup habitat)	250		4
Cabin furnishings (sleep, cook, meeting, work, bathroom areas)	500	prime habitat (also includes laundry & shower)	4
Cabin furnishings (sleep, cook, meeting, work, bathroom areas)	500	backup habitat (also includes laundry & shower)	4
Workstations/Communcations/Local Mission Control	250	Full mission control capability onboard	
Fission-Thermionic Reactor, 100 kw (main power)	2500	Topaz class (russian launched to LEO)	2
Emergency Sustaining Solar Cell Panel Power System (2kw)	250	GaAs Focused 20% efficiency array	4
Gaseous O2/H2 Fuel Cell Storage System (Emergency Storage)	500	14-day at 5% power	4
LOX Generation plant (prime, high production rate)	2000	ilmenite (reduction) reduction	5
LOX Generation plant (backup, low production rate)	500		5
LOX Storage System (lunar product) & refridgeration	1000		4
Cryogenic CO2 processor	100		
4 EVA suits plus repair parts/materials	300		2
Ice bulk melter & bio filter	300	small demo system in case ice is found	3
Water storage tank	100	fuel cell product storage + excess for ice	3
Water cracking unit (gaseous O2/H2 production)	100	for fuel cell power	5
Utility truck	1500	NMH-electric, 600 km range, 4 ton capacity	5
Hydroponics facility	600	capable of sustaining 6 individuals indefinitely	4

Lunar Surface Consumables (non-regenerative)

6-months reserve FD food	500	use microwave for cooking; 300 g/day/person	2
6-months reserve water (assuming 80% physio-chemical recycle)	1728		3
Non-recyclable personal consumables	540	personal toiletries etc.	3
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Cabin ECLSS system hardware	100		3
General repair kit	100	patch kit, lights, duct tape, tool kit etc.	
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3

Personnel

3 persons @ 100 kg max	300		1
personal clothing @ 30 kg/person x 3 persons	90		2
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms) (including propellant) 72750 Spacecraft "Dry" mass + payload

Propellant Mass Budget

LOX (oxidizer)	**220927**	Earth-to-Moon plus abort reserve	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**55217**	Round trip	2
Total Propellant Budget:	276144.45		

Total Spacecraft Mass (fully loaded with fuel & oxidizer) 348894.45

Propellant Mass Fraction 0.79

Transportation Cost (earth to LEO staging)	$ 2,302,703,370	$6600 per kilogram to LEO (500 km, 51-deg)	
Hardware Cost (purchase price)	$ 41,940,000	$1500 per kilogram for hi-tech hardware	
Engineering & Test	$ 40,000,000		
Total: Project Development & Conduct:	$ 2,384,643,370		
Contingency (10%)	$ 238,464,337		
Profit (10%)	$ 238,464,337		
Total Project Budget	$ 2,861,572,044	To establish permanent lunar base and allow for return to LEO.	
Sale of Lunar LOX (returned from moon)	$ 314,330,500	Based on assumption of NO lunar ice	
Sale of Lunar LOX (returned from moon)	$ 1,062,435,000	Based on assumption of DISCOVERY of lunar ice	
Profit (if NO lunar ice available)	$ (2,547,241,544)	at end of one-cycle	
Profit (if lunar ice IS available)	$ (1,799,137,044)	at end of one-cycle	

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Earth Return and Rendesvous (1-pass aerobrake re-insertion to LEO)	**Dry Mass Estimate (kilograms)**	**Notes:**	**Precision** **1=Good** **5=WAG**

Orbit Transfer/Landing Vehicle

Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
LOX (Lunar Product) ###	**230000**	**Product for sale in LEO: made on the Moon**	2
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Personnel

3 persons @ 100 kg max	300		1
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms)	240806	Spacecraft "Dry" mass + payload

(including propellant)

Propellant Mass Budget

LOX (oxidizer)	**179160**	Made on the Moon	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**44790**	(Brought from Earth) ****	2
Total Propellant Budget:	223950		

Total Spacecraft Mass (fully loaded with fuel & oxidizer) 464756

Propellant Mass Fraction 0.48

Transportation Cost (earth to LEO staging)	$ -	Already paid for	
Hardware Cost (purchase price)	$ -	Already paid for	
Engineering & Test	$ -	Already paid for	
Total: Project Development & Conduct:	$ -		
Contingency (10%)	$ -		
Profit (10%)	$ -		
Total Project Budget	$ -	Already paid for	

*** if ice is discovered, LH2 for return trip need not be brought from earth
this completely pays for up mission

Peary Crater Expedition Lunar LOX/Ice Reconnaissance/Recovery Mission
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Study 3 Second Mission (lo ELV cost) Earth LH2.xls

Lunar Landing Mass Budget: SECOND mission **Study 3: low ELV cost to LEO** **Note: LH2 return supply brought from earth**	**Dry Mass Estimate (kilograms)**	**Notes:**	**Precision** **1=Good** **5=WAG**

Orbit Transfer/Landing Vehicle

Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
LH2 for Earth Return	**44790**	In this scenario, LH2 must be brought from earth	2
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Lunar Surface Consumables (non-regenerative)

6-months reserve FD food	500	use microwave for cooking; 300 g/day/person	2
6-months reserve water (assuming 80% physio-chemical recycle)	192	Bring LH2 only; recombine with lunar LOX	3
Non-recyclable personal consumables	540	personal toiletries etc.	3

Personnel

3 persons @ 100 kg max	300		1
personal clothing @ 30 kg/person x 3 persons	90		2
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms) (including propellant)	56918	Spacecraft "Dry" mass + payload

Propellant Mass Budget

Tank Mass: 3196

LOX (oxidizer)	**172849**	Brought from Moon *******	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**43201**	up portion only, brought from earth	2
Total Propellant Budget:	216049.3444		

Total Spacecraft Mass (fully loaded with fuel & oxidizer)	272967.3444
Propellant Mass Fraction	0.79

Transportation Cost (earth to LEO staging)	$ 290,369,515	$6600 per kilogram to LEO (500 km, 51-deg)	
Hardware Cost (purchase price)	$ -	already amortized	
Engineering & Test	$ -	already amortized	
Total: Project Development & Conduct:	$ 290,369,515		
Contingency (10%)	$ 29,036,951		
Total Project Budget	$ 319,406,466	To make another trip to the lunar base	
BUT: Profit comes from sale of returned LOX	$ 125,733,119	Sale of excess LOX at $500/lb under going rate	
Profit	$ (193,673,347)	Profit on the next mission	

Peary Crater Expedition Lunar LOX/Ice Reconnaissance/Recovery Mission
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Study 4 Second Mission (lo ELV cost)LunarLH2.xls

Lunar Landing Mass Budget: SECOND mission **STUDY 4: Low ELV TRANSPORT COSTS TO LEO** **Note: LH2 Supply Lunar Derived** **Orbit Transfer/Landing Vehicle**	**Dry Mass Estimate (kilograms)**	**Notes:**	**Precision** **1=Good** **5=WAG**
Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Lunar Surface Consumables (non-regenerative)

6-months reserve FD food	500	use microwave for cooking; 300 g/day/person	2
6-months reserve water (assuming 80% physio-chemical recycle)	192	Bring LH2 only; recombine with lunar LOX	3
Non-recyclable personal consumables	540	personal toiletries etc.	3

Personnel

3 persons @ 100 kg max	300		1
personal clothing @ 30 kg/person x 3 persons	90		2
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms) (including propellant)	12128	Spacecraft "Dry" mass + payload

Propellant Mass Budget

Tank Mass: 1140

LOX (oxidizer)	**36830**	Brought from Moon *******	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**9205**	up portion only, brought from earth	2
Total Propellant Budget:	46035		

Total Spacecraft Mass (fully loaded with fuel & oxidizer)	116326.9248
Mass budget from earth	1712
Propellant Mass Fraction	0.40

Transportation Cost (earth to LEO staging)	$ 5,649,600	LH2 (derived from lunar ice) brought from moon	
Hardware Cost (purchase price)	$ -	already amortized	
Engineering & Test	$ -	already amortized	
Total: Project Development & Conduct:	$ 5,649,600		
Contingency (10%)	$ 564,960		
Total Project Budget	$ 6,214,560	To make another trip to the lunar base	
BUT: Profit comes from sale of returned LOX	$ 424,973,317	Sale of excess LOX at $500/lb under going rate	
Profit	$ 418,758,757	Profit on the next mission	

Peary Crater Expedition Lunar LOX/Ice Reconnaissance/Recovery Mission
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Study 5 second Mission (hi-ELV cost)EarthLH2.xls

Lunar Landing Mass Budget: SECOND mission
STUDY 5: CONSERVATIVE TRANSPORT COSTS TO LEO
Note: LH2 return supply brought from earth

Orbit Transfer/Landing Vehicle

Orbit Transfer/Landing Vehicle	**Dry Mass Estimate (kilograms)**	**Notes:**	**Precision 1=Good 5=WAG**
Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
LH2 for Earth Return	**44790**	In this scenario, LH2 must be brought from earth	2
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Lunar Surface Consumables (non-regenerative)

6-months reserve FD food	500	use microwave for cooking; 300 g/day/person	2
6-months reserve water (assuming 80% physio-chemical recycle)	192	Bring LH2 only; recombine with lunar LOX	3
Non-recyclable personal consumables	540	personal toiletries etc.	3

Personnel

3 persons @ 100 kg max	300		1
personal clothing @ 30 kg/person x 3 persons	90		2
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms) (including propellant) 56918 Spacecraft "Dry" mass + payload

Propellant Mass Budget

Tank Mass: 3196

LOX (oxidizer)	**172849**	Brought from Moon *******	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**43201**	up portion only, brought from earth	2
Total Propellant Budget:	216049.3444		

Total Spacecraft Mass (fully loaded with fuel & oxidizer) 272967.3444

Propellant Mass Fraction 0.79

Transportation Cost (earth to LEO staging)	$ 580,739,029	$6600 per kilogram to LEO (500 km, 51-deg)	
Hardware Cost (purchase price)	$ -	already amortized	
Engineering & Test	$ -	already amortized	
Total: Project Development & Conduct:	$ 580,739,029		
Contingency (10%)	$ 58,073,903		
Total Project Budget	$ 638,812,932	To make another trip to the lunar base	
BUT: Profit comes from sale of returned LOX	$ 314,332,797	Sale of excess LOX at $500/lb under going rate	
Profit	$ (324,480,135)	Profit on the next mission	

Peary Crater Expedition Lunar LOX/Ice Reconnaissance/Recovery Mission
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Study 6 Second Mission (hi ELV cost) LunarLH2.xls

Lunar Landing Mass Budget: SECOND mission
STUDY 6: High ELV TRANSPORT COSTS TO LEO
Note: LH2 Supply Lunar Derived

Orbit Transfer/Landing Vehicle

	Dry Mass Estimate (kilograms)	**Notes:**	**Precision 1=Good 5=WAG**
Inflatable Cabin (rigid setting 4m dia. X 12m)	302	urethane inflation, dual bulkhead, twin cell	2
Cabin facilities	500	cockpit, crew quarters, mess, latrine etc.	4
Airlocks (5 @ 50 kg each)	250	dual egress, center isolation	3
Exoskeleton (carbon-carbon)	600	LEO/EVA assembly	4
Landing Gear (deployable)	300	gas actuated, gas shock/damper	4
Primary propulsion (5 x RL-10) pre-assembled minus tank pipes	1000	LOX/RP-1 Isp = 300 s (conversion)	3
Piping for main propulsion buss to tankage	200		4
LOX storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LOX storage vessels (lunar abort provision)	300		3
LOX storage vessels (lunar product)	1000	Can return both LOX and H20	3
LH2 storage vessels (lander system)	1000	Required for lunar landing + Abort Return	3
LH2 storage vessels (LEO return/ lunar abort)	300	Round trip	3
Metabolic Oxygen reserve (1 month, 6 persons)	370	LOX	2
Chemical CO2 scrubber reserve (1 month, 6 persons)	611	anhydrous 4x14 LIOH	2
Metabolic Oxygen reserve tankage	53	carbon/epoxy	3
Cabin ECLSS system control/processing hardware	100	Standard space shuttle design	3
Cabin pressurization (air) plus leakage reserve & EVA provision	380	3:1 recharge factor	2
RCS system	100	Attitude control, docking approach	5
RCS consumables (MMH/N2O4)	200	hydrazine/nitrogen tetroxide hypergolics	5
GNC/Avionics	200	Full up mission simulator & auto control planning	4
Communications (audio, lo-res comp. Video, high def. Stills,data)	150	Includes live position telemetry from DSN	4
Aerobrake (earth return)	1000	Primary earth approach velocity brake	5
Cargo bay flip-out container & pneumatic deploy system	500	four to six utility pods (large capacity)	4

Lunar Surface Consumables (non-regenerative)

6-months reserve FD food	500	use microwave for cooking; 300 g/day/person	2
6-months reserve water (assuming 80% physio-chemical recycle)	192	Bring LH2 only; recombine with lunar LOX	3
Non-recyclable personal consumables	540	personal toiletries etc.	3

Personnel

3 persons @ 100 kg max	300		1
personal clothing @ 30 kg/person x 3 persons	90		2
personal items @ 30 kg/person x 3 persons	90		2

Structure + Payload Mass Budget for Landing (kilograms) (including propellant)	12128	Spacecraft "Dry" mass + payload

Propellant Mass Budget

Tank Mass: 1140

LOX (oxidizer)	**36830**	Brought from Moon *******	2
LH2 (fuel; Isp = 400; mix ratio: 4.02:1)	**9205**	up portion only, brought from earth	2
Total Propellant Budget:	46035		

Total Spacecraft Mass (fully loaded with fuel & oxidizer)	116326.9248
Mass budget from earth	1712
Propellant Mass Fraction	0.40

Transportation Cost (earth to LEO staging)	$ 11,299,200	LH2 (derived from lunar ice) brought from moon	
Hardware Cost (purchase price)	$ -	already amortized	
Engineering & Test	$ -	already amortized	
Total: Project Development & Conduct:	$ 11,299,200		
Contingency (10%)	$ 1,129,920		
Total Project Budget	$ 12,429,120	To make another trip to the lunar base	
BUT: Profit comes from sale of returned LOX	$ 1,062,433,293	Sale of excess LOX at $500/lb under going rate	
Profit	$ 1,050,004,173	Profit on the next mission	

Appendix B: 2003 Launch Rate Chart*

Launch costs for the past 30 years have remained in the $5000 to $15,000 per pound range to LEO due largely to use of expendable launchers which incur large manufacturing costs to rebuild another rocket for each launch. The table below is presented largely as a comparison with Appendix D which shows that rates between 1997 and 2003 have changed little. The Russian Proton remains the most viable likely contender for the missions described above.

LAUNCHER	LBS TO LEO	RANGE OF LAUNCHER COSTS	PER LB MIN/MAX
Proton ***	44,200	$75-$95 M	$1697/$2149
Ariane5	39,600	$150-180 M	$3788/$4545
Sea Launch	35,000	$75-$95 M	$2143/$2714
Zenit 2	30,000	$35-$50 M	$1167/$1667
LM-3B	29,900	$50-$70 M	$1672/$2341
Ariane 4	21,000	$100-$125 M	$4762/$5952
Atlas 2	19,050	$90-$105 M	$4724/$5512
Delta 3	18,280	$75-$90 M	$4103/$4923
Soyuz	5,400	$35-$40 M	$2273/$2597
Delta 2	11,220	$45-$55 M	$4011/$4902
LM-2C	7,040	$20-$25 M	$2841/$3551
Athena	04,350	$22-$26 M	$5057/$5977
Rockot	04,100	$12-$15 M	$2927/$3659
Taurus	03,100	$18-$20 M	$5806/$6452
Pegasus	03,300	$12-$15 M	$3636/$4545
START	01,543	$5-$10 M	$3240/$6481
Space Shuttle**	40,000	$600M	$15000

Average Cost-per-LB to LEO: $3632-$4587

* As published by the Center for Strategic and Budgetary Assessments

** Space Shuttle rates are based on average flights per year and the cost of maintaining shuttle launch and support services at Kennedy Space Center (currently provided by contractor United Space Alliance) and Johnson Space Center. Actual costs to the government may be higher still.

*** The price quoted for the Soyuz and Proton is what the Russian Organizations have said they would be willing to sell them for. However, US law forbids the marketing of these (and other Russian) vehicles for US launchers for any price less than 93% of the price of comparable US launch vehicles. For US customers, the cost of a Soyuz would be about $65 million (93% the cost of an Atlas 2), while the Proton would be about $149 million (93% the cost of a Titan IV).

Appendix C: Space Nuclear Auxiliary Power (SNAP) Status

In the mid-1990s, the Department of Energy (DoE) conducted work on the fabrication of General Purpose Heat Source Radioisotope Thermoelectric Generators (GPHS-RTG's) and 157 Radioisotope Heater Units (RHU's) for NASA's Cassini mission to Saturn. RTG's directly convert the heat from the decay of the radioisotope Plutonium-238 (Pu-238) into electricity without any moving parts; they have been employed successfully on more than 20 spacecraft of long-duration missions. DoE supported NASA in developing environmental documentation and performing safety testing for the safety analysis reports required for the launch approval process of Cassini. The Cassini mission ultimately flew successfully with its RTG.

About this same time DoE and NASA officials signed a Supplemental Agreement to the basic Memorandum of Understanding on radioisotope power systems for the Mars Pathfinder mission. DoE is to provide three Lightweight Radioisotope Heater Units (LWRHU's) from its inventory (these are actually spares from the Galileo and Ulysses missions) for this upcoming launch. DoE also began preparing a Final Safety Analysis Report on the LWRHU's for the Mars Pathfinder mission.

Similarly, for NASA's Pluto Express mission, DoE engineers and scientists studied advanced converter technologies to provide high-efficiency and lightweight power sources. DoE engineers also initiated technology development work to investigate and demonstrate the viability of advanced power converters using thermophotovoltaic, alkaline metal, and Stirling engine technologies. In conjunction with JPL, DoE explored the use of a bimodal (power/propulsion) space reactor system to support NASA's New Millennium spacecraft program. In a joint program with the Air Force, DoE developed design concepts for three bimodal space reactor power systems.

During the mid-1990's DoE staff also participated in an interagency technical working group on space reactor systems sponsored by the Defense Nuclear Agency to review its Topaz International Program. This program is centered on a thermionic space power system developed in the former Soviet Union, called the Topaz II. Unlike RTG's, the Topaz reactor had moving parts like a ground nuclear power plant. At the component level, under the DoE-managed 40-kilowatt (of electric power) thermionic space reactor program, technicians completed the initial evaluation of a single-cell thermionic fuel element that is to double the power of past designs. At the basic research level, work continued on the cesium effects on bulk and surface conductivity of seal insulators and collector sheath insulators and the cesium plasma erosion of interelectrode gap ceramic spacers.

These earlier studies have now led to NASAs "Prometheus Initiative" which seeks to develop radioisotope-based systems (i.e. RTGs) and nuclear fission-based systems (i.e. SNAP, or Space Nuclear Auxiliary Power reactors). Under this initiative, NASA and DOE will jointly develop Radioisotope Power Systems (RPS) that will focus on two technologies, the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and the Stirling Radioisotope Generator (SRG). Funding for this initiative is still under discussion on the Hill.

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Date of Birth: December 7, I952

Birthplace: Pittsburgh, Pennsylvania, USA

Education:

Rensselaer Polytechnic Institute, B.S. Civil Engineering, 1974
Rensselaer Polytechnic Institute, M.Eng., Structural Engineering, 1975
University of Texas, PhD., Structural Engineering, 1980

Licenses:

Registered Professional Engineer, District of Columbia (Washington DC) #749007986

Professional Affiliations and Awards

American Institute of Aeronautics & Astronautics (1987-present)
American Society of Civil Engineers (1980-present)
Society of Naval Architects and Marine Engineers (1999-2001)
Tau Beta Pi & Chi Epsilon National Engineering Honorary Fraternities

Vice-Chairman, ISARC 2002 (International Symposium on Automation and Robotics in Construction)
Technical Chairman, ASCE Robotics 2000 Conference
Member, CII FIATECH advisory committee (2001-present)
Chairman, ASCE Committee on Field Sensing and Robotics (1999-2001)
Member, CII Committee on RFID (radio frequency identification) (1998-2001)
Member, CII Committee on Wireless Ad-hoc Networks (1997-1998)
Member, AIAA Task Committee on Aerodynamic Decelerator Systems (1989-1991)

IAARC Tucker-Hasegawa Award [2002] for international advancement in construction automation.
Willard Bascomb Quadrennial Prize for Underwater Exploration [3D mapping technology] (2001)
Silver Medal, U.S. Dept. of Commerce [for engineering excellence in novel technology] (2001)
ACI Structural Research Award [development of seismic damage model for bridges] (2000)
ACI Structural Research Award [design of novel precast seismic building system] (1997)
BFRL Communications Award [novel precast seismic building system invention] (1997)
BFRL Communications Award [structural performance during 1989 Loma Prieta Earthquake] (1990)
BFRL Communications Award [seismic design of bridge columns] (1988)
Bronze Medal, U.S. Dept of Commerce [structural performance during 1985 Mexico earthquake](1987)
T.Y. Lin Award, ASCE [resolution of problem with pre-cast box girder bridge design] (1985)
Wason Medal, American Concrete Institute [non-destructive evaluation of concrete] (1985)
Who's Who Among Rising Young Americans

Corporate Affiliations:

President, Stone AeroSPACE (1998-present)
President, Piedra-Sombra Corporation, Inc. (2001-present)
Chairman, Cis-Lunar Development Laboratories, Inc. (1987-present)
President, U.S. Deep Caving Team, Inc. (1980-present)
Member, Board of Directors of LunaCorp, Inc. (1989-2003)
Member, Board of Directors, Space-Tech Shoes, Inc. (2002-present)

Author of 120+ engineering publications
Author of more than 100 exploration-related publications
Author of 2 books on exploration, including the June 2002 release by Time-Warner of “Beyond the Deep” -- a saga of U.S. exploration efforts to go deeper into the earth than has ever been reached before by humans.

Patents

Digital Waterproof Lap Counter	US 4,932,045
Breathing Apparatus Mouthpiece	US 4,964,404
Breathing Apparatus Gas Routing Manifold	US 4,974,585
Breathing Apparatus	US 5,127,398
High Speed, Amplitude-Variable Thrust Control	US 5,271,226
High Speed, Amplitude Variable Thrust Control Method	US 5,431,342
Breathing Apparatus Mouthpiece	US 5,368,018

Patents Pending

Gas Control Manifold for Life Support System	S/N 09/227,517
Carbon Dioxide Filter for Life Support System	S/N 09/227,524
Registered Location Radiation Intensity Scanner	60/159,481 (provisional)
Three Degree-of-Freedom Telescoping Geometry Scanner	60/106,828 (pending)

Engineering Experience:

President
Stone AeroSPACE
Gaithersburg, Maryland
1998-present

This organization was founded in 1998 to address advanced robotic and deployable system applications for manned and unmanned exploration. The organization has two projects currently underway: the design, development, and flight test of a novel ultra high surface-to-mass ratio manned re-entry system; and the development of autonomous underwater mapping and life discrimination systems for use in hydrothermal springs (a project known as DEPTHX). The organization consists of a network of world-class consultants in structural, mechanical, electrical, and aerospace design combined with computer architecture and embedded systems designers and software programmers. As a whole, the team specializes in the design of novel, computer controlled gagetry, from hand-held to vehicle-sized. The core team that has been assembled for the current projects was responsible for the development of the spectacularly successful 3D real-time mapping system used by the National Geographic Society to create the world’s first fully three-dimensional cave map in 1999. The DEPTHX project has received 3-year funding and is underway at this time.

Leader
Construction Metrology and Automation Group
National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland
1980 - 2003

Dr. Stone is the leader of the Construction Metrology and Automation group at NIST in Gaithersburg, Maryland. Current major program management at NIST includes the development of real-time field sensing systems in support of the CONSIAT Program (Construction Integration and Automation Technologies). This is a $2M/year program focused on bringing robotics (fully autonomous machinery) and IT to the construction industry.

Previous project management included the development of the National Construction Automation Testbed (NCAT -- a government/industry consortium to investigate data uplink issues for construction sites and to develop augmented simulation systems for component tracking and vehicle control at construction sites), and the National Advanced Manufacturing Testbed (NAMT) program in construction automation (in which a 30-ton full-scale bridge crane was remotely monitored using live, 3D data-driven augmented reality, wireless video and audio, and high speed net trunking). This latter capability was selected for inclusion in the Highway One NGI Congressional demonstration for the Next Generation Internet.

Dr. Stone has 20 years of professional research, design, integration, and deployment experience in structures, dynamics, and mechanical systems design (including stress analysis, 3D design, assembly, and kinematics analysis) as well as extensive experience in scientific software development, data visualization, world sensing systems, 3D laser radar and sonar data processing, and automated machinery design.

His current research at NIST includes the development of Next Generation LADAR systems; through-wall impulse radar tracking systems; laser radar-based terrain modeling systems, real-time discrete component laser tracking systems, the development of wireless intelligent sensing, control, and simulation systems for construction machinery, and the development of fully autonomous construction crane "pick and place" systems. In the latter project work is underway to develop robust 3D laser radar real-time docking procedures for automated placement of construction components. Dr. Stone has also worked on a number of space-related projects for the Office of Technology Assessment and for NIST including the conversion of the Space Shuttle external tank into an orbiting industrial laboratory, studies for Congress on the international space station, and the development of an ultra-fast, precision space vehicle reaction control thruster.

Chairman of The Board
Cis-Lunar Development Laboratories, Inc.
Gaithersburg, Maryland
1980 - Present

Dr. Stone founded Cis-Lunar Development Laboratories in to design and develop advanced life support apparatus for Undersea and Space exploration. He has 20 years experience in the design of advanced life support apparatus and manned underwater systems. Key inventions and products developed by Dr. Stone at Cis-Lunar include:

- **1980:** The first fully composite diving apparatus. Developed in collaboration with NASA, this was a dual-tank backpack utilizing S-glass composite pressure vessels running at 375 bar. Special tank valves and regulator conversions were developed. These were used in the 1981 and 1984 Huautla expeditions. See the website: http://www.usdct.org/usdct_expeditions/rio_iglesia.htm

- **1987:** MK-1 rebreather. Developed between 1984 and 1987. This was the first fully redundant closed cycle life support architecture. It was an original design that included twin gas processors, four onboard computers, and the ability to manually cross connect the two halves of the system in the event of emergencies underwater. It weighted 100 kg and had a range of 48 hours. This was used dramatically on December 3 and 4 of 1987 when Dr. Stone spent 24 hours continuously underwater using the prototype device. First self-contained diving apparatus to make use of lithium hydroxide as a carbon dioxide absorbent. First rebreather to have a hydrophobic absorbent canister. See the website: http://www.usdct.org/usdct_expeditions/wakulla1987.htm

- **1987:** Portable, Variable-depth Underwater Decompression Habitat. This was a six-person system that used a novel hemispherical inflatable living quarters ballasted by 10,000 kg of lead. The system was 1 ton positively buoyant and connected to a deep anchor through a manual chain hoist that could be used

to raise or lower the habitat. In this manner returning exploration teams at Wakulla Springs could perform decompression in dry comfort. See the webs
http://www.usdct.org/usdct_expeditions/wakulla1987.htm
http://www.usdct.org/photo_gallery/pg1987.dir/habitat_in.htm

- **1989:** MK-2 rebreather. A much more compact and improved dual-rebreather that included six onboard computers, a head-up display, and a more compact gas management system. First twin counterlung rebreather. The MK-2 had a range of 12 hours. The prototype weighed 50 kg.

- **1991:** MK-3 rebreather. An improved version of the MK-2 with more reliable electronics, automatic diluent addition and a new CO2 absorbent canister design. Nine units were produced and field tested.

- **1994:** MK-4 rebreather. Substantially improved version of the MK-3 including field-tested mouthpiece that converted from open to closed circuit operation. New control electronics, significant software upgrades including operational real-time decompression status and real-time selection of oxygen setpoint. See the website: http://www.usdct.org/usdct_expeditions/huautla1994.htm

- **1996:** MK-5P Mod 0 rebreather. Commercial production 40 units. Substantial improvements over the MK4, including condensate minimizing design; rapid field maintenance features (including access to oxygen sensors, removal and replacement of CO2 canister, and removal of condensate); and vastly improved electronics resulting in a size reduction of nearly 50% of that of the MK4. See the website: http://www.usdct.org/rebreathers.htm

- **1998:** MK-5P Mod 1 rebreather. Substantial improvements to the MK5-Mod-0 based on user field use. Included substantial improvements in the software operating system, backpack design, offboard gas connection and selection system; decompression download (tissue tension model); decompression planner; and data download capabilities. See the website: http://www.usdct.org/Updates/dec23.htm and http://www.usdct.org/Updates/dec29.htm

- **1999:** 3D Digital Wall Mapper. A revolutionary submarine imaging system that uses a helical sonar array and an inertial guidance system to image the complete geometry of a submerged tunnel. The system mounts to a modular diver propulsion vehicle that can be controlled by a towed diver. The diver can program the system while underwater. The internal control network includes 8 computers that interface to 37 sensors and two servo-driven pitch/roll canard diving planes. Software includes onboard control system; laptop-based data download program; and Silicon Graphics based visualization in 3D. See the website: http://www.usdct.org/mapper.htm and http://www.usdct.org/Updates-Jan/jan10.htm and http://www.usdct.org/Updates-Feb/feb07.htm During December 1998 through February 1999 the 3D Digital Wall Mapper collected 10,000,000 3D data points inside Wakulla Springs. These data have not only formed the basis for the world's first fully three-dimensional cave map but have also become a benchmark test data set for automated meshing algorithms operating on sparse 3D point cloud data.

- **1999:** Long Range Diver Propulsion Vehicle (aka the "Fat Man"). Designed for operation at depths of up to 150 meters the Fat Man used nickel metal hydride industrial batteries and a custom designed motor to achieve a burn time of greater than 6-1/2 hours at 1.2 meters/second for a fully loaded diver. The system weights 63 kg in air but is absolutely neutral in water. This was the main propulsion system for the Wakulla 2 expedition. See the website: http://www.usdct.org/scooters.htm

- **1999:** Dual MK5-P system. Two versions of fully redundant rebreathers were developed for the Wakulla 2 expedition. These included a vehicle mounted version that employed a novel breathing hose quick-connect designed by Stone (http://www.usdct.org/Updates/dec21.htm) and a second design that placed both MK5 rigs in a single backpack (http://www.usdct.org/Updates-Feb/feb06.htm). Both systems have a range of 20 hours at 150 meters.

- **1999:** Modular Floating Decompression Habitat. This was a novel implementation of commercial saturation diving equipment. A series of modular micro-barges was assembled and a standard saturation decompression habitat and personnel transfer capsule were mounted on top. A special launch system with dual pneumatic hoists was developed to handle deployment and docking of the pressurized personnel transfer capsule. This system was used for 32 3D mapping missions during the National Geographic Society expedition to Wakulla Springs, Florida in 1999. See the website: http://www.usdct.org/Updates/dec08.htm and http://www.usdct.org/Updates-Feb/feb20.htm

Expeditionary Experience:

Dr. Stone is recognized as a world authority on cave exploration. He has led or participated in 45 international caving expeditions in the last 33 years during which he has spent more than six years in foreign countries, mostly in southern Mexico, working in the extremely deep caves of the Sierra Mazateca (Sistema Huautla) and Sierra Juarez (Cueva Cheve) regions. He has logged a phenomenal 334 days based from subterranean camps, many greater than a kilometer deep. The longest single stay was 18 days at Camp 6, -1353m deep in the Sotano de San Agustin, Mexico. Dr. Stone has been the principal architect behind the exploration of Mexico's Huautla Plateau and the exploration of Sistema Cheve. He is credited with initiating the Technical Diving revolution first by introducing safe procedures for work at great depths underwater in caves[1] and later reducing these techniques to practice in the 1989 book entitled “The Wakulla Springs Project.” Dr. Stone’s invention of advanced closed cycle life support systems for cave diving culminated in the historic 1994 National Geographic Society expeditions to Huautla (which reached -1475 meters depth) and the 1999 expedition to Wakulla Springs, Florida where the first fully 3D cave map was produced. In the spring of 2003 he led a 3-month international expedition to Cueva Cheve that netted a depth of -1484 meters at a distance of 9.3 kilometers from the nearest entrance – a point presently considered to be the most remote location reached inside the Earth by humans. He is the current president of the United States Deep Caving Team, Inc., a non-profit organization dedicated to fielding multi-disciplinary teams to explore the world's most challenging caves. He will co-lead the ***2004 Sistema Cheve*** expedition, a 2-month international expedition that will seek to establish a new record for the world's deepest cave. Some of the more significant projects during the past 23 years are summarized here:

1980 Rio Iglesia Expedition

In 1980 he led the U.S. team on the four-month Rio Iglesia Expedition to the Huautla Cave System of southern Mexico, during which the team reached a point 1222m beneath the surface, establishing the Huautla System as the world's third deepest cave. Dr. Stone made a solo dive in Li Nita Cave at a depth of –1030m which led to a connection with the Sotano de San Agustin, thus achieving the –1222m depth.

Expedition Website: http://www.usdct.org/usdct_expeditions/rio_iglesia.htm

1981 Agua de Cerro Expedition

In 1981, as leader of the Agua de Cerro Expedition, Dr. Stone dove 285m into a flooded corridor at the bottom of the Huautla System (-1353m) in an effort to reach an air filled continuation leading towards the center of the plateau. This was the longest exploratory dive ever achieved at the bottom of a deep cave and marked the first use of fully composite filament wound Scuba apparatus – a new system designed by Dr. Stone and NASA. 4-1/2 month expedition.

Expedition Website: http://www.usdct.org/usdct_expeditions/agua_de_cerro.htm

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[1] Beginning with the 1985 expedition to Wookey Hole in England which made use of Trimix breathing gas; followed by the regular use of heliox 80/20 during the International Blue Holes Expedition in the summer of 1987 and culminating with the National Geographic Society expedition to Wakulla Springs, Florida in the fall of 1987 during which more than 100 dives were made using heliox followed by nitrox and pure oxygen decompression. The procedures developed for the latter project became the basis for Technical Diving worldwide.

1982 Mount McKinley Ice Caves Expedition

In 1982 Dr. Stone was the co-leader of a climbing/exploration team to Mount McKinley, Alaska during which he directed an exploration program of the ice caves of the Muldrow Glacier. On the same expedition he was a member of the summit assault team which successfully reached the top of McKinley after 40 days on the mountain. In the fall of 1982 he served as the cartographer in a five person team of specialists called in by the Puerto Rican government to develop a national park at the Rio Camuy Cave System on the northwest corner of the island.

1984 Pena Colorada Expedition

In the spring of 1984 he led the multi-national Pena Colorada Expedition in an effort to dive through the artesian springs at the base of the Huautla Plateau and to explore 10 kilometers upward towards the point reached in 1981. The expedition, which was in the field for four months, eventually succeeded in reaching a point more than four kilometers into the mountain. Twenty five percent of this distance was totally underwater, a factor which was to make this the most logistically complex cave exploration project in history. Among the many "firsts" achieved by this expedition was the establishment of long duration, remote subterranean operations bases beyond a series of flooded corridors (used for 27 days) and the use of pre-conditioning simulations to train the team in the techniques of cave diving.

Expedition Website: http://www.usdct.org/usdct_expeditions/penacolo84.htm

1985 International Expedition to Wookey Hole, Somerset, England

During the summer of 1985 he was a member of a six person team attempting to resolve the internal hydrology of the Mendip Hills of Somerset, Great Britain. Entering via the artesian springs at Wookey Hole, the team dived through 600m of underwater tunnels and set a five day subterrenean camp at a point two kilometers from the entrance. Using composite diving apparatus and a 36% helium gas mixture the team extended the limit of exploration to a depth of 68m underwater in the final tunnel before discovering an impassable restriction. This was the first use of helium mixtures at a remote underground exploration site.

1987 National Geographic Society Wakulla Springs Expedition

In the fall of 1987 he served as expedition leader for the 3-month Wakulla Springs Project, an international effort to study and chart the unknown reaches of Wakulla Springs, Florida (the site originally believed to be the "fountain of youth" by Ponce de Leon). This project was the focus of substantial advances in life support technology and cave diving techniques, including the use of habitats, diver propulsion vehicle-borne sleds, multi gas decompression, and near-saturation work at average depths in excess of 100m. The team successfully explored and mapped 3.3 kilometers of flooded galleries, the largest of which measured 50m wide by 20m tall. The project achieved national media attention and a documentary film aired in Britain in August of 1988 and later on National Geographic Explorer in the United States.

Expedition Website: http://www.usdct.org/usdct_expeditions/wakulla1987.htm

1988, 1989, 1990, and 1991 Cueve Cheve Expeditions

From 1988 through 1991 Dr. Stone participated in four expeditions to Cueva Cheve, Oaxaca, Mexico during which time it became the deepest cave in the Western Hemisphere at - 1386m. Bill was involved with the initial exploration of the cave below the 800m level to its present depth (at a point 11 kilometers traverse distance from the entrance) and with the initial establishment of all three underground camps used to further the exploration front. He assumed logistics planning responsibilities for the diving effort in 1991 which netted the current depth.

Training Missions 1992-1993 for the San Agustin Expedition

In 1992 and 1993 Dr. Stone organized and led two 2-month training missions for the San Agustin Expedition. These involved participants from six nations and represented the first extensive use of closed cycle life support apparatus (rebreathers) for use in cave diving. During these two years the team logged more than 200 underwater missions and 30 hyperbaric chamber runs to depths as deep as 110 m, swimming distances in excess of 4 km, and for durations in excess of 6 hours continuously underwater. Decompression was calculated using onboard software. There were no incidences of DCS (bends). All rebreather missions were carried out with a perfect safety record. The 1993 effort also involved a realistic expedition simulation at 1200 m elevation in the Cueva Infiernillo in northern Mexico. During this exercise rebreathers were broken down into modular packs, transported over 5 km of rugged terrain and to the bottom of the 72 km long Sistema Purificacion (for which Cueva Infiernillo is the lower entrance). The MK-4 rebreathers were re-assembled at a week-long underground camp and used for eight flawless exploratory missions. The team discovered 500 m of underwater galleries which reached a depth of 57 m. This extended the depth of the system to 954 m, making it the 5th deepest cave in the Western Hemisphere.

1994 National Geographic Society San Agustin Expedition

From January 15th through June 1, 1994 (4-1/2 months) Dr. Stone led an international team of explorers to the Huautla Cave system in Oaxaca, Mexico. Using MK4 rebreathers, the team succeeded in exploring through the San Agustin Sump (an underwater tunnel beginning at a depth of -1353m) and ultimately reaching a depth of -1475m. The team spent a total of 44 days based from underground camps below -1000m. This established the Huautla System as the 5th deepest cave system in the world. The end of the cave, at -1475m and beyond 700m of flooded tunnels at the -1353m level, is presently considered the most remote point yet reached by humans inside the earth. The expedition story was published in the September 1995 issue of National Geographic Magazine as well as the Washington Post Magazine and Outside Magazine. It has also appeared in several elementary school science textbooks, Italy's Focus Magazine, and has been translated into six foreign languages including Russian and Japanese.

Expedition Website: http://www.usdct.org/usdct_expeditions/huautla1994.htm

1999 National Geographic Society Wakulla 2 Expedition

In 1999 Dr. Stone led the 3-month National Geographic Society Expedition to Wakulla Springs, Florida, USA. This was the most technical cave diving expedition ever fielded and it resulted in the production of the world's first 3D cave map. For this expedition the Cis-Lunar engineering design team (including Bill Stone, Nigel Jones and Mike Stevens) invented a series of novel inventions including a 3D digital autonomous underwater imaging system; a dual version of the MK5 rebreather which had a range of 20 hours at 100m depth underwater; the world's longest range diver propulsion vehicle (6-1/2 hour travel time at 1.2 meters/second); and a modular field-deployed floating hyperbaric decompression habitat and a mobile personnel transfer capsule that would retrieve returning exploration teams from –30m under pressure. The team developed custom decompression procedures that involved laptop computer interrogation of the MK5 backpack to generate the decompression habitat portion of the surfacing schedule – something that had never before been accomplished. The team conducted 32 deep level missions inside Wakulla Springs with average bottom times of 4.5 hours at 100m water depth. The expedition was the first to make routine scientific diving below –100m underwater. For several months the team fielded a significant mission each day for three days in a row followed by a day of maintenance whereupon the cycle would be started again. More than 23 kilometers of underwater tunnels were mapped in 3D. The resulting data include 10,000,000 survey points. This project was featured as the cover story in National Geographic Adventure magazine (Summer 1999) and as a documentary film on the National Geographic Explorer TV Channel (under the title "Mapping the Labyrinth"). A total of 234 MK5 rebreather dives were logged during the Wakulla 2 expedition.

Expedition Website: http://www.usdct.org/

See also:

http://www.nationalgeographic.com/adventure/9905/profile.html [interview]
http://www.nationalgeographic.com/voices/ax/frame.html [Wakulla 2 online]

2001 Inner Space Odyssey Expedition

From January 15, 2001 to April 30, 2001 Dr. Stone co-led the 2001 Inner Space Odyssey Expedition. The objectives of the expedition were to reach a point deeper inside the earth than humans have ever gone. The expedition involved an Olympic-class international team comprised of deep vertical cavers, big wall climbers, and cave divers. The expedition succeeded in mapping 3.8 kilometers of new galleries inside the Huautla Plateau, the Sierra Juarez, and the Sierra Tamaulipas. Significantly, the resurgence springs for the Huautla Cave system were cracked at a distance of 1059m upstream from the spring rising using MK5 closed cycle rebreathers designed by Dr. Stone. The tunnel, which reached a maximum water depth of 65m, surfaced inside the east wall of the Pena Colorada canyon, thus opening a "back door" to the heart of the Huautla plateau. A future 4-month expedition will be required to exploit this breakthrough, owing to the logistics of setting up a long duration camp beyond such a tremendous underwater distance.

2003 Sistema Cheve Expedition

Dr. Stone led a 55-person team from 9 countries on a 3-month effort to be the first exploration party to crack -2000 meters depth in a natural cavern. The team spent 33 days below the -1,000 meter level of Sistema Cheve in Oaxaca, Mexico. The lead team, of which Dr. Stone was a member, dived through 500 meters of flooded tunnels at the -1360 m level before emerging in an air-filled river canyon. This was followed to a depth of -1484 m at a point 9.3 kilometers from the nearest entrance to a point where a ceiling collapse blocked the way forward. This point presently represents the most remote location yet reached by humans inside the planet. As of September 2003 National Geographic Society is reviewing images and maps acquired by the expedition for a potential story in the main NGS Magazine.

Dr. Stone is a fellow of the Explorers Club (New York) and the National Speleological Society. In 1980 he recieved a commendation from the United States Embassy in Mexico City for assistance he and the U.S. team rendered in the evacuation from minus 600m of members of the 1980 Polish Expedition to the Sotano de San Agustin, Mexico. This was at the time the deepest rescue in the history of speleology.

Dr. Stone was a semi-finalist in the NASA astronaut selection process in 1989 and is a licensed private pilot.

He has written more than 100 articles relating to exploration and equipment development, was the principal author of the book The Wakulla Springs Project, and has authored portions of two other books. In July 2002 Time-Warner published Beyond the Deep, Dr. Stone's book describing 30 years of exploration on Mexico's Huautla Plateau.

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"NIST Research in Construction Sensing and Automation," presentation to Disney Imagineering Research and Development representative, July 18, 2003, Gaithersburg, MD.

"Some Issues Relating to Performance Evaluation of LADARs," 2003 Performance Metrics Conference, NIST, Gaithersburg, MD. September 16-18, 2003.

"Tucker-Hasegawa Lecture," ISARC 2003 Invited Keynote Plenary Lecture, Eindhoven, the Netherlands, September 21-24, 2003.

2002

“Achieving General Construction Automation: Myth and Reality,” Carnegie-Mellon University, September 21, 2001.

“Achieving General Construction Automation: Myth and Reality,” University of Texas Civil Engineering Seminar, October 23, 2001.

“ NIST Construction Automation Program” Night Vision Lab, Fort Belvoir, December 17, 2001.

“NIST Construction Automation Program,” Irvine Sensors, Inc., January 24, 2002.

“NIST Construction Automation Program,” Riegl Systems, Inc., Horn, Austria, February 20, 2002.

“NIST Construction Automation Program,” CSEM, Zurich, Switzerland, February 20, 2002.

“NIST Construction Automation Program,” University of Siegen, Siegen, Germany, February 25, 2002.

“NIST Construction Automation Program,” Briefing for Carnegie-Mellon University Research Initiative Team, March 12, 2002.

“Laser Radar Fundamentals,” University of Texas at Austin, two lectures for the Sensors in Civil Engineering Course, March 21, 2002.

“Laser Radar Seminar Series,” NIST, June 18-20, 2002.

“Towards the Ultimate Construction Site Sensor,” ISARC, September 24, 2002.

2001

“Object Identification Using Bar Codes Based on LADAR Intensity,” International Symposium on Automation and Robotics in Construction (ISARC-2001), Krakow, Poland, September 10-12, 2001.

“NIST Research in Smart Chips” CII-FIATECH Interested Parties Workshop, June 26-27, 2001, Gaithersburg, MD., June 26, 2001,

“NIST 3D Range Imaging Program,” CII-FIATECH Interested Parties Workshop, June 26-27, 2001, Gaithersburg, MD., June 27, 2001

“NIST 3D Range Imaging Program,” NIST Laboratory Director’s Tour, June 22, 2001, NIST, Gaithersburg, MD.

“NIST 3D Range Imaging Program,” Defense Advanced Research Projects Agency, June 21, 2001, DARPA, Arlington, VA.

“NIST Construction Automation Program,” Federal Highway Administration (FHWA), June 14, 2001

“NIST Construction Automation Program,” Office of Nuclear Energy, Science and Technology, Department of Energy (DOE), October 24, 2000

“NIST Construction Automation Program,” National Aeronautics and Space Administration (NASA), December 18, 2000

“NIST Construction Automation Program,” General Services Administration (GSA) December 14, 2000

William C. Stone: Computer Literacy:

Structural/Mechanical Analysis:

Package	Use	Skill Level
COSMOS/M	General non-linear/dynamic FEM analysis w/optimization, full 3D	fluent
COSMOS/Works	General purpose FEM tightly coupled to SolidWorks	fluent
STAAD-Pro	Production Structural Frame Analysis	intermediate
ANSYS	General non-linear/dynamic FEM	functional (used substantially in past years)
PATRAN	General non-linear/dynamic FEM	functional (used substantially in past years)
NASTRAN	General non-linear/dynamic FEM	functional (used substantially in past years)
DYNAMIC DESIGNER	Windows version of ADAMS (mechanical dynamics simulation) tightly coupled to SolidWorks	novice

Design

Package	Use	Skill Level
ACAD 14/2000	General CAD package 2D & 3D	fluent
SOLIDWORKS 2001	Parametric CAD package, 3D	fluent

Data Visualization

Package	Use	Skill Level
Walls3D	3D vector network analysis, statistics, and viz package	fluent
Maple	Symbolic Mathematics	intermediate
SGI / GL	SGI-based graphics programming language (precursor to Open/GL)	functional (used substantially in past years)
IDL	General purpose data viz program	novice
Open/DX	General purpose data viz program	novice
MathCAD	General purpose symbolic math and viz program	novice

Image Processing & Illustration

Package	Use	Skill Level
Adobe Photoshop	manual image processing	fluent
Adobe Illustrator	commercial level graphics package	fluent
Adobe Premier	Commercial digital video editing	intermediate
MS Powerpoint	slide generator	fluent
DreamWeaver	web authoring tool	fluent
Corel	general drawing package	fluent

Software (programming)

Package	Use	Skill Level
MS Fortran 90	general scientific programming language	fluent
MS Visual Basic	general purpose GUI builder and coding language	intermediate
MS C++	general programming language	novice

Desktop Publishing & General Office/Report/Proposal Generation

Package	Use	Skill Level
QUARK EXPRESS	commercial desktop publishing program	fluent
MS Word	general word processing	fluent
EXCEL	general spreadsheet calculations	fluent
KALEIDAGRAPH	general spreadsheet calculations	fluent
Adobe Distiller	portable document generator	fluent
Adobe Acrobat	protable document reader	fluent
FAST TRACK	project management	fluent

Foreign Language Translation

Package	Use	Skill Level
SYSTRAN	spanish document translation	fluent
MicroTAC	spanish document translation	fluent

Operating Systems

WINDOWS	most software	fluent
MAC	some graphics packages	fluent
UNIX	real-time and data viz programs	intermediate

Networking

Package	Use	Skill Level
Eudora Pro	email	fluent
TelNET	remote login	fluent
CUTE-FTP	high speed file transfer	fluent
Netscape	web browser	fluent
Exceed 3D	X-windows emulator	intermediate