

Human Lunar Destiny: Past, Present, and Future

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Abstract. This paper offers conceptual strategy and rationale for returning astronauts to the moon. NASA's historic Apollo program enabled humans to make the first expeditionary voyages to the moon and to gather and return samples back to the earth for further study. To continue exploration of the moon within the next ten to fifteen years, one possible mission concept for returning astronauts using existing launch vehicle infrastructure is presented. During these early lunar missions, expeditionary trips are made to geographical destinations and permanent outposts are established at the lunar south pole. As these missions continue, mining operations begin in an effort to learn how to live off the land. Over time, a burgeoning economy based on mining and scientific activity emerges with the formation of more accommodating settlements and surface infrastructure assets. As lunar activity advances, surface infrastructure assets grow and become more complex, lunar settlements and outposts are established across the globe, travel to and from the moon becomes common place, and commerce between earth and the moon develops and flourishes. Colonization and development of the moon is completed with the construction of underground cities and the establishment of a full range of political, religious, educational, and recreational institutions with a diverse population from all nations of the world. Finally, rationale for diversifying concentrations of humanity throughout earth's neighborhood and the greater solar system is presented.

INTRODUCTION

As NASA continues to move forward with the construction of the international space station, space policy makers are increasingly pondering the notion of permanently returning humans back to the moon with the ultimate goal of sending crewed missions to Mars. Development of space transportation capability between the earth and moon, establishment of lunar outposts and settlements, and the development of an extra-terrestrial economic base are logical next steps in humanity's deliberate march to celestial destinations in the solar system and beyond.

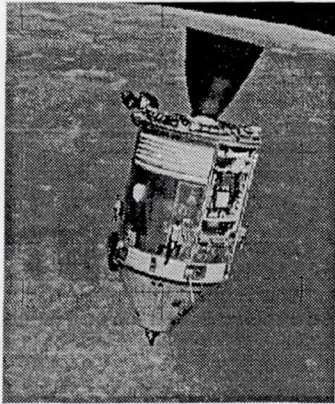
To achieve these goals, advanced technologies for all major onboard spacecraft systems must be developed and tested in an environment that allows engineers and astronauts to gain the necessary operational experience and confidence necessary to proceed with more ambitious missions to Mars and beyond. Due to its proximity to Earth, the moon allows such an environment and as a spin-off, will provide the first new territory for human growth and expansion since the end of the nineteenth century.

Aside from the eventual economic benefits such an expansion will bring, a significant return from scientific activities may also result from continued investigations on the lunar surface. These include a clearer understanding of the impact history of comets in near-earth space, better knowledge about the composition of the lunar mantle, past and present solar activity, lunar ice at the poles, and the history of volatiles in the solar system. Commercial opportunities include the extraction of oxygen, water, and metals from the lunar soil, as well as materials processing.

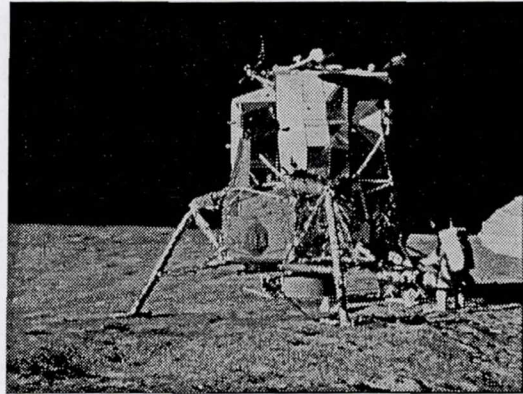
To gain a broader perspective of lunar endeavors, a brief look at the accomplishments of Apollo, a snapshot of conceptual near-term return missions to the moon, and a vision for an emerging lunar infrastructure and independent economy are all explored in the following pages of this paper.

THE PAST

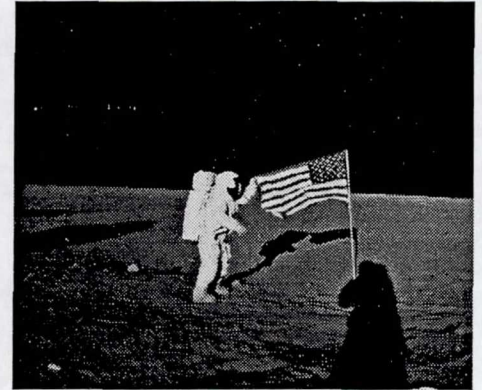
Project Apollo, born out of the political climate of the 1960's, gave humanity its first opportunity to venture past the boundaries of its home planet to its closest neighbor—the moon. During the Apollo “wonder years”, from 1968 to 1972, twenty-seven Americans made the journey to the moon. Of those twenty-seven, twelve landed on the surface of the moon, planted their flags and footprints on its surface with all of them returning safely to the Earth.



Apollo Command/Service module in orbit around the moon with exposed science payload bay.



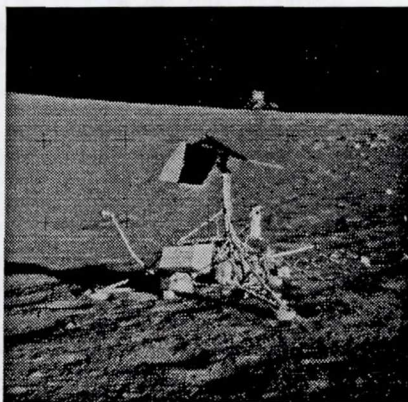
Apollo 12 Lunar Landing at north rim of Surveyor Crater – Ocean of Storms



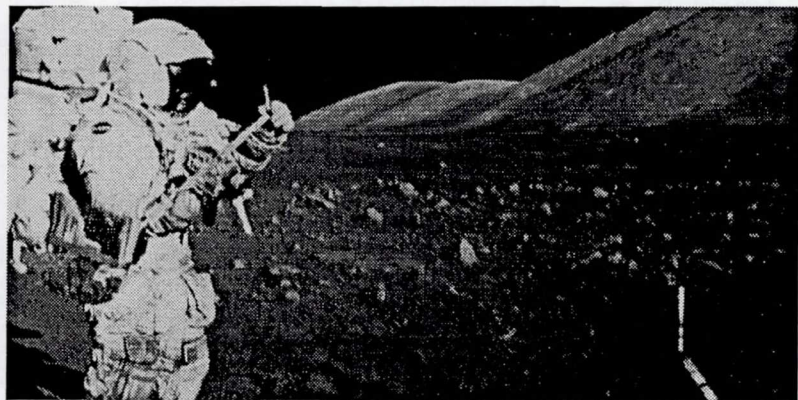
Apollo 12 crew plants the Flag

FIGURE 1: Apollo spacecraft and astronauts during the first lunar expeditionary phase of lunar exploration

In addition to the remarkable achievement of landing crews on the moon, the Apollo lunar program realized many other accomplishments including deployment of scientific instruments on the lunar surface, gathering surface samples, taking thousands of photographs, live television broadcast of surface activities, demonstration of precision landing, salvaging parts from a previously-deployed robotic spacecraft. Together with mission control, the astronauts confronted and overcame a host of problems which could have jeopardized their missions and even prevented their safe return to Earth. Some of the more noteworthy incidents included the 1201 and 1202 alarms during the descent of the Apollo 11 crew enroute to the first lunar landing, the broken-off Apollo 11 ascent arm switch, the lightning strike on the Apollo 12 launch vehicle during its first moments of flight, the rupture of the oxygen tank onboard the Apollo 13 service module, the problems encountered with the Apollo 14 radar altimeter, and the loss of scientific surface data during an Apollo 15 EVA when the power/data cable was accidentally damaged. In spite of these events, the astronauts were successful in performing some entertaining and sometimes inspirational acts including, the simultaneous dropping a feather and a lunar rock in honor of Galileo's contributions to the understanding of gravity, played golf, left graffiti written in the soil, and made playful reference to the first extra-terrestrial used car lot.



Surveyor III lander at Surveyor crater
Note: Apollo 12 LM in background on crater rim

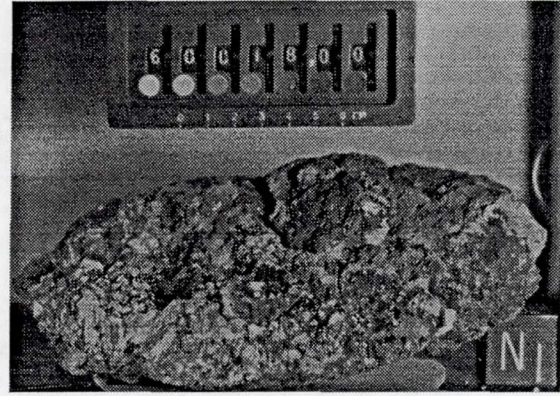


Apollo 17 Taurus-Littrow site

FIGURE 2: Apollo 12 Lunar module precision landing and field work at the Apollo 17 Taurus-Littrow site

The samples of lunar soil and rock that the astronauts brought back to Earth rendered new understanding about the moon's chemical composition, rock sample surface features, and lunar soil cohesion properties. Scientists learned more about the lunar environment including seismic activity, the solar wind, and micro-meteor impacts. In addition, laser beams originating from the earth were bounced off of mirrors that were left on the lunar surface by three of the visiting astronaut crews in order to determine precise distances between the two celestial bodies. Finally, more was

learned about the events that shaped the surface of the moon from the examination of surface craters, ejecta, and lava flows—both from on orbit and at the landing sites.



Sample 60018 – Station 10 at the Apollo 16 Descartes landing site... ... and at the Lunar Receiving Laboratory following the mission

FIGURE 3: Lunar sample as it was found on the moon and after its earth arrival for scientific study

Perhaps the most significant achievement of the Apollo landing missions was the ability of the astronauts to perform unprecedented exploration of the lunar surface—first on foot for the first three missions, and by LRV on the last three missions which allowed the astronauts to range up to 5 km away from their stationary Lunar Module. During their EVA excursions the astronauts explored flat-plain maria, valleys, high-land mountainous regions, craters, and impact basins.

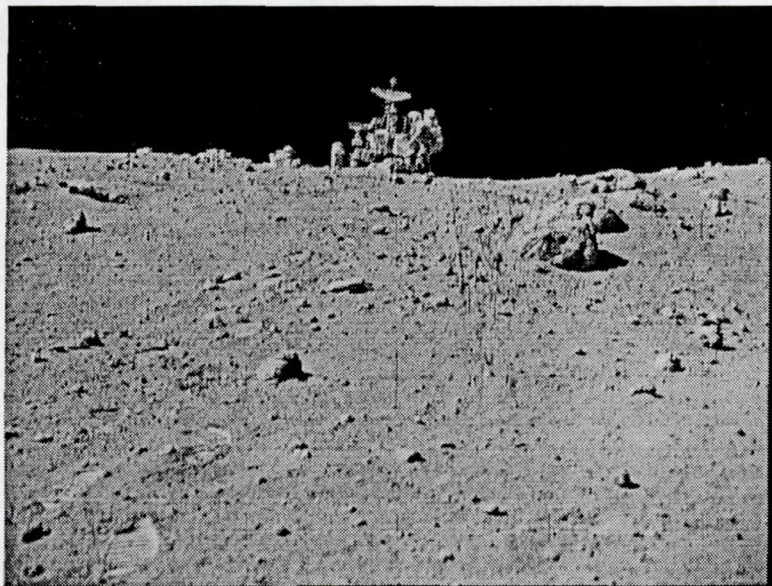


FIGURE 4: Exploring the lunar surface in the LRV at the North Ray crater – Apollo 16 Descartes landing site

Following a massive buildup of manpower, scientific research, development and fine-tuning of the spacecraft hardware, the Apollo program was discontinued resulting in the cancellation of the last three missions (Apollo's 18, 19, and 20). Factors which led to program cancellation included the fact that the US was embroiled in a very costly and unpopular war in Vietnam, loss of interest, on the part of the American public, in continuing moon landings following the successful landing of Apollo 11, the meeting of political goals of the cold-war era, and the overall expense of the program. Since the Apollo 17 lunar mission in 1972 when two astronauts visited the Taurus-Littrow highlands, no astronauts have since journeyed to the moon.

The Lunar Environment

As leaders and policy-makers consider the possibility of returning humans to the moon for the first time in over thirty years, questions must be raised about the reasons for going back. The moon is, after all, a world quite unlike Earth. It has an atmosphere approximately 14 orders of magnitude less than earth composed primarily of neon, hydrogen, helium (from the solar wind), and argon derived from the radioactive decay of potassium—so it is essentially a vacuum. The moon is seismically active with over 500 moonquakes per year registering from between 1 and 2 on the Richter scale. It is bombarded by approximately 30,000 micro-meteors per year. Unlike the earth, the moon has a very weak magnetic field so it cannot effectively shield biological organisms from the harmful effects of solar and galactic radiation. Its lunar day/night cycle is 672 hours (28 Earth days), and its mean surface temperature ranges from 107° C (225° F) during the day to -153° C (-243° F) at night. In spite of these differences, the moon offers an abundance of natural resources including magnesium, titanium, chromium, iron, zinc, nickel, and cobalt. In addition, oxygen can be extracted from the lunar regolith and used as a breathable atmosphere. And, data from the recent *Clementine* and *Lunar Prospector* missions suggest significant depositions of water/ice in craters at the north and south poles in quantities ranging from 100 million to 1.3 billion metric tons. If in fact this is true, water—an essential ingredient to sustaining life, could be mined and used for a variety of purposes including drinking water, breathable oxygen, extraction of hydrogen for rocket propellant, growing crops, and a host of other uses.

As access to space becomes less expensive, as known reserves of metals dwindle, and as world-wide populations continue to increase, the prospect for expansion to Earth's nearest neighbor becomes more and more attractive. Finally, as mission planners contemplate sending humans to Mars and the outer planets of the local solar system, the moon will provide an operational testbed where spacecraft and surface systems can be developed and tested in order to build confidence in technologies critical to the successful completion of crewed deep-space missions.

THE PRESENT

Several strategies for returning humans to the moon in order to continue scientific study and development of surface structures are being considered. One of these strategies, known as the Gateway Architecture study, was conceived and developed by engineers at the Johnson Space Center and is presented in this paper.

The Gateway Architecture is a conceptual study whose goal is to return humans to the moon within the next ten to fifteen years while providing development of core capabilities that will enable human missions to Mars. Such core capabilities include the development of advanced systems and technologies that can be developed and tested in a near-earth operational environment. Such an environment will provide operational experience for autonomous deep space operations, planetary surface operations, and a Mars analog operations base at the lunar south pole.

A significant return from scientific activities may result from investigations on the lunar surface. These include a clearer understanding of the impact history of comets in near-earth space, better knowledge about the composition of the lunar mantle, past and present solar activity, lunar ice at the poles, and the history of volatiles in the solar system. Commercial potential includes the extraction of oxygen, water and metals from the lunar soil, and materials processing.

Several important assumptions are made at the outset to enable the development of the mission architecture. These include deferring the development of high-capacity launch systems by utilizing existing launch vehicle systems, and utilizing lunar libration point number one and the International Space Station (ISS) as transfer nodes between the two planetary surfaces. In addition no long-term commitment regarding extensive lunar surface infrastructure is made while initial transportation capabilities are established allowing for the future expansion of science and commercialization activities. Finally, a crew of four can be transported to and from the moon for expeditionary missions or for extended stay missions and returned to earth. Any cargo to the lunar surface is transported separately from the crew and is predeployed on the lunar surface before the crew arrives.

The Gateway Architecture is composed of a suite of elements which make it possible to send and return humans from the moon. These elements include a lunar depot called the L1 Outpost that is located at L1, the Crew Transfer Vehicle (CTV) which ferries the crew from the International Space Station to the Gateway, a high-energy injection

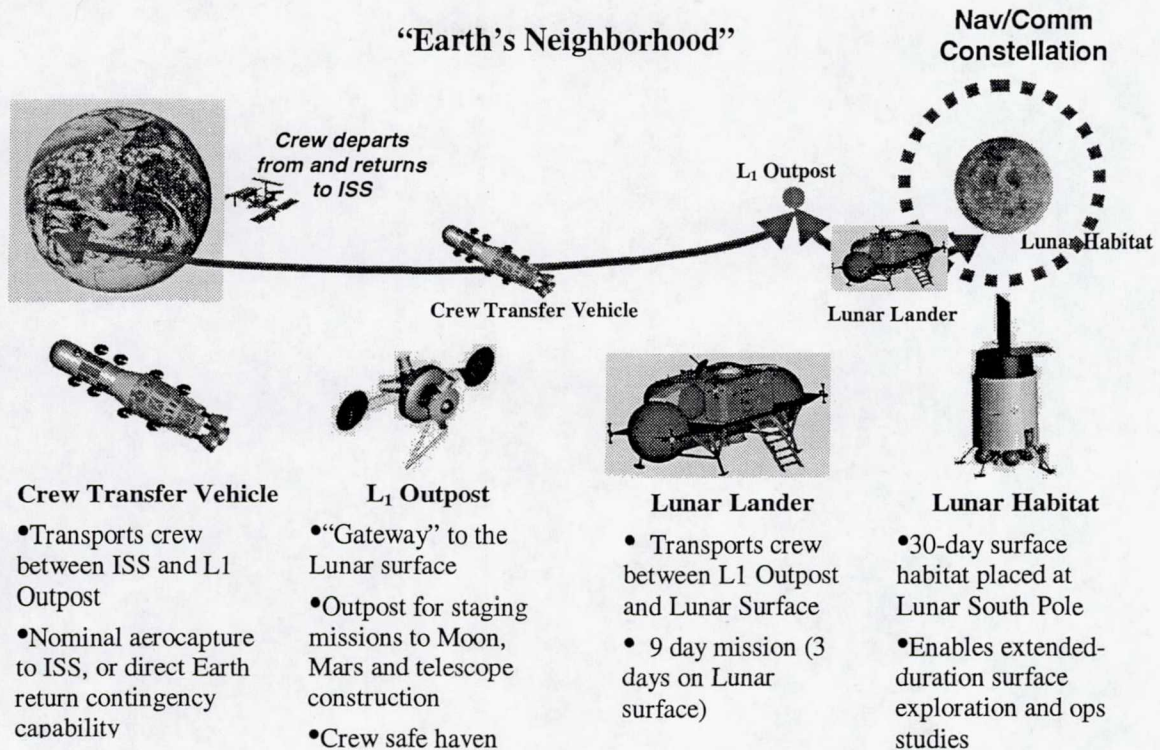


FIGURE 5: Elements of the Gateway Architecture study—one possible near-term strategy for returning humans to the moon within the next ten to fifteen years

stage which provides an initial boost for the CTV, the L₁ Lunar Hab Lander which supports the crew for 30-days at the lunar south pole, the L₁ Lunar Lander which performs three-day expeditionary missions to any point on the lunar surface or 30-day extended missions at the lunar south pole, and high-efficiency solar electric propulsion transfer vehicles which spiral the L₁ Outpost and landers to the L₁ staging area. Other supporting elements of the architecture include the Space Shuttle which launches the crew to the ISS and the L₁ Outpost to low earth orbit, the ISS which houses the CTV and serves as the nominal terminal for returning lunar astronauts, the Delta-IV expendable launch vehicle which brings the CTV and landers to low earth orbit, the Global positioning system for navigation, and a constellation of satellites in low lunar orbit to aid in lunar navigation and communication with earth. The figure above depicts how the Gateway Architecture elements are deployed for to perform the mission.

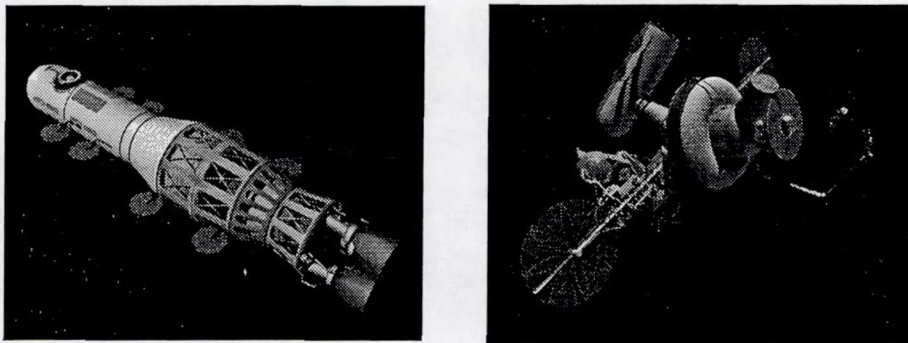


FIGURE 6: Crew enroute from ISS to L₁ Outpost on CTV, CTV docked at the L₁ Outpost at Lunar L₁

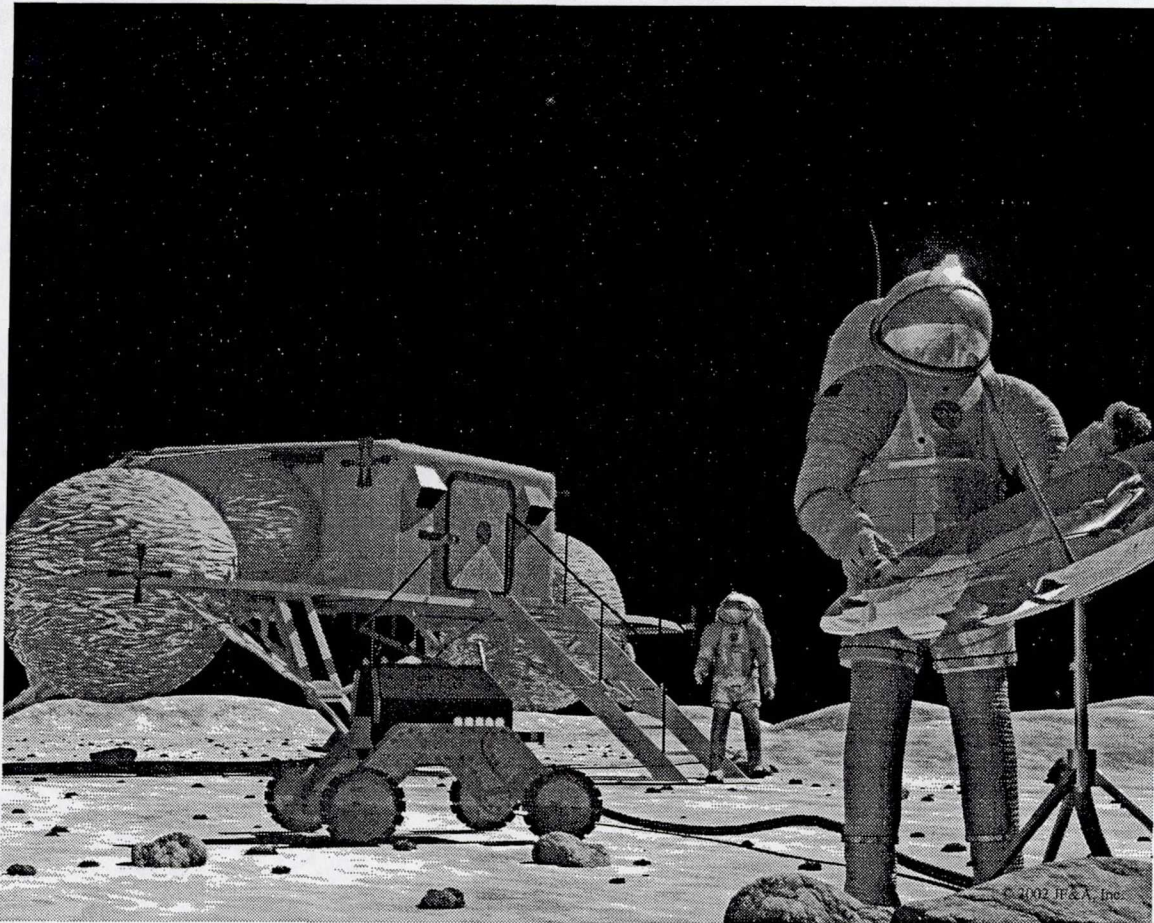
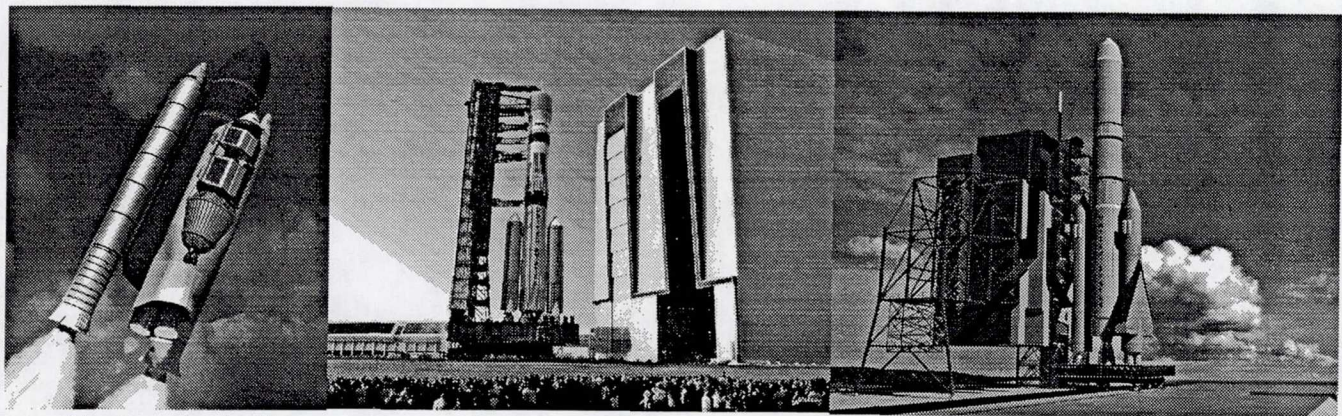


FIGURE 7: Astronauts performing surface tasks near L1 Lunar Lander during scheduled EVA

This Gateway strategy has the added benefit of being able to provide the staging point for the deployment and maintenance of an array of telescopes that would be located at earth/solar L2 and may even provide the initial staging point for human missions to Mars. As demand grows for lofting larger payloads to the moon, launch vehicles that can provide economical, routine, and safe heavy-lift capability will be needed. Figure 8 below depicts several proposed concepts for heavy-lift launch vehicles that could be used in support of continued development of lunar surface infrastructure and advanced human missions.



Shuttle-derived HLV

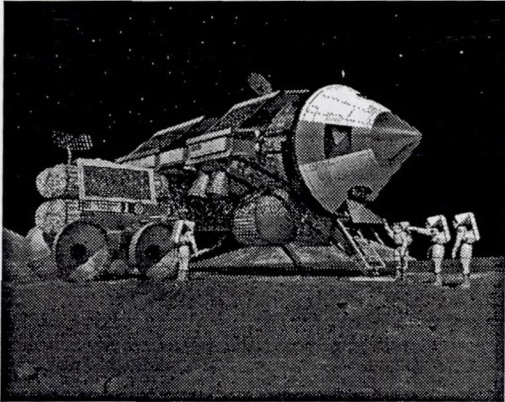
Magnum HLV

HLV with flyback booster

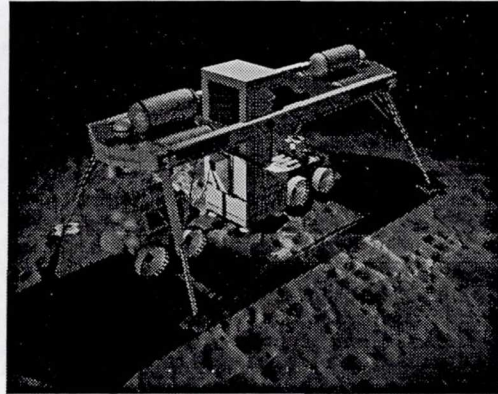
FIGURE 8: Proposed heavy-lift launch vehicles needed in support of advanced human missions

TRANSITION TO THE FUTURE

As the space transportation infrastructure begins to mature and larger payloads are brought to the lunar surface with greater frequency, a shift toward increasing levels of autonomy will take place. The first lunar entrepreneurs and colonists will seek ways to “live off the land” through the use of indigenous natural resources. Most likely, oxygen processing from lunar regolith, water extraction from the polar regions, and propellant refueling facilities will be the first and most basic in-situ infrastructures that will help to make other lunar operations more profitable and less of a risk. The emplacement of these initial infrastructures will also decrease the amount of Earth logistical resupply necessary to permanent settlements of crews and equipment. With refueling infrastructure in place, landers will be able to increase the payload mass they can bring to the lunar surface since they would no longer be required to bring along fuel for the return trip.



Propellant Refueling Capability



Oxygen Processing Facility

FIGURE 9: Processing facilities that will enable the first lunar entrepreneurs and colonists to “live off the land”

As short-term astronaut crews who are primarily preoccupied with surface exploration and sample processing, give way to long-term scientific and entrepreneurial business interests, more permanent and robust shelters and lodging will be required. To this end a variety of camp or outpost strategies might be employed including fixed or mobile habitat modules such as the ones pictured below in figure 10. Also strategies for radiation protection and continued logistical supply, for items that cannot yet be produced on the moon, will have to be employed. Radiation countermeasures might include module burial in the lunar regolith or on-board shielding. The latter would be more payload intensive due to its increased mass, but would require no additional processing when emplaced on the lunar surface. Module burial, on the other hand would not require as much payload to be placed on the lunar surface, but would require construction equipment (i.e., tractors and bulldozers with scoops) to bury the module. Also, long-term onboard systems such as life support will have to be very robust. Basic consumables such as air, water, and some food growth will be required to cut down on the amount and frequency (expense) of logistical resupply.

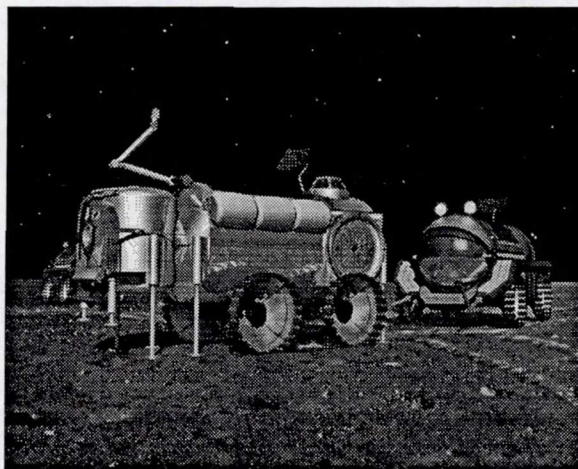


FIGURE 10: Setting up a lunar base camp in support of initial long-term lunar operations

Living accommodations aboard these first permanent habitat structures will be adequate, but not spacious or luxurious. They will be similar to conditions endured by the early pioneers who wintered over at the south pole, by submariners on nuclear powered subs, and by cosmonauts and astronauts on the MIR space station. Mission durations will be similar in length to stays aboard the ISS (90 days). In many ways these early pioneers will experience the most hardship as lunar outposts are developed. They will be required to endure stressful situations including hardware failures, long working hours, a rigid lifestyle, shortages of food, water, and air, and being away from friends and family in a hostile environment for extensive periods of time.

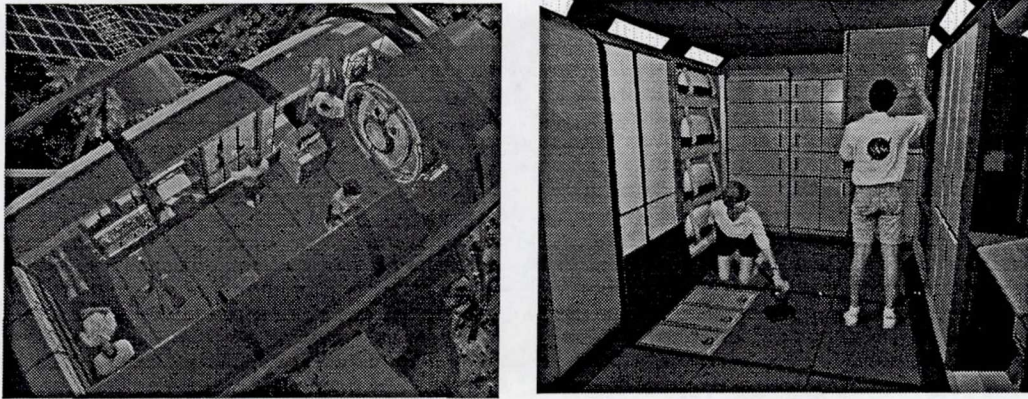


FIGURE 11: Permanent living quarters, while adequate, will not be spacious or luxurious

Other than extraction of lunar materials for basic life support, initial surface activity may center around basic lunar science (i.e. placing/monitoring of seismic activity, placement/monitoring of solar wind collectors, gathering of lunar surface samples for on-site lab analysis, monitoring of solar activity, and initial deep space astronomy). Early surface infrastructure may also include systems test bed development to gain confidence in the technologies that will be used in support of eventual Mars missions. Testing of life support systems with closed loop processing of food, air, and water will be developed. Also testing will be conducted to improve the technologies leading to precision landings, connectivity of pressurized habitation and laboratory modules which are placed on the surface in separate flights, and autonomous spacecraft operations which require little or no intervention from earth-based mission control support personnel.

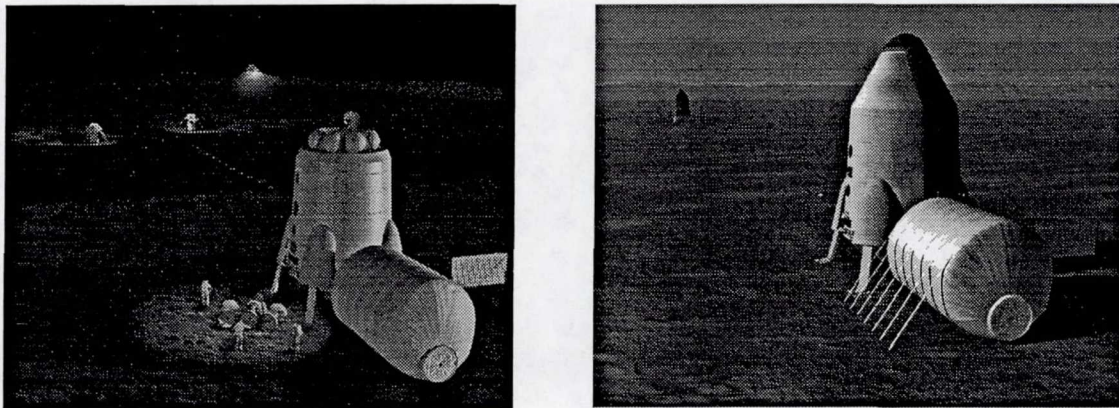


FIGURE 12: Lunar assets used as system testbeds to gain confidence in technologies used for Mars missions

With the passage of time, a burgeoning lunar base infrastructure will emerge. This infrastructure will include habitation facilities, communication systems, surface transportation, advanced life support with some resupply, propellant mining for refueling of landers, a lunar launch infrastructure, maintenance and research facilities, and initial mining operations. At this stage, life on the moon will be analogous to similar infrastructure that exists in Antarctica with an established supply line of goods and services beginning to flow between Earth and Moon. Living

conditions will become less stressful, and while they will become more comfortable, they will still be somewhat utilitarian.

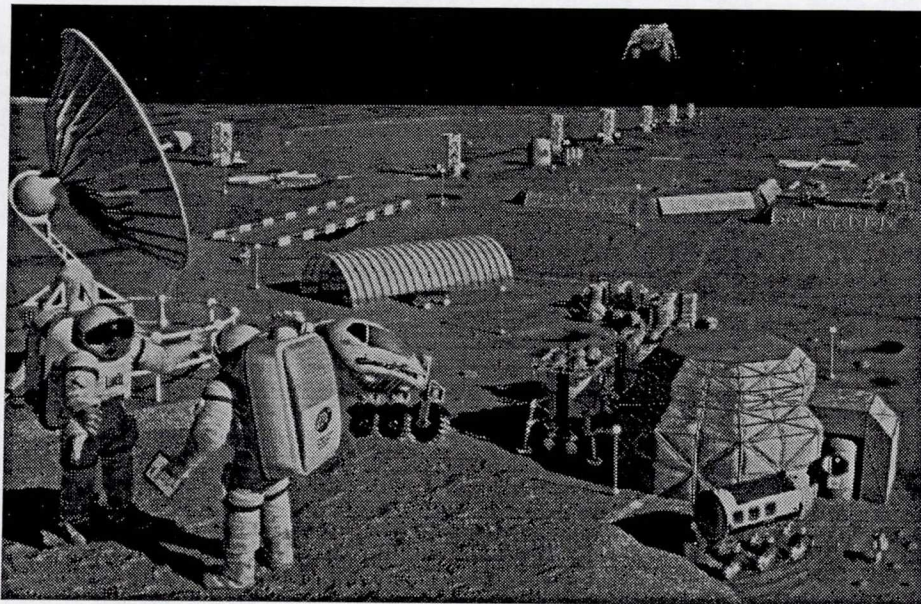


FIGURE 13: With the passage of time a burgeoning lunar base infrastructure will emerge

In addition to the emerging commercial infrastructure, a complete array of large scientific observatories will be put in place at various points on the lunar surface including the near side, poles, and far side of the moon.. Reflecting telescopes with very large mirrors for deep space optical and infrared astronomy could be erected, large-scale X-ray observatories could be constructed to study black holes and other high-energy phenomena, and arrays of antenna dishes for deep space radio astronomy could be set up on the moon's backside where interference from radio signals emanating from Earth would not disturb or distort observations.

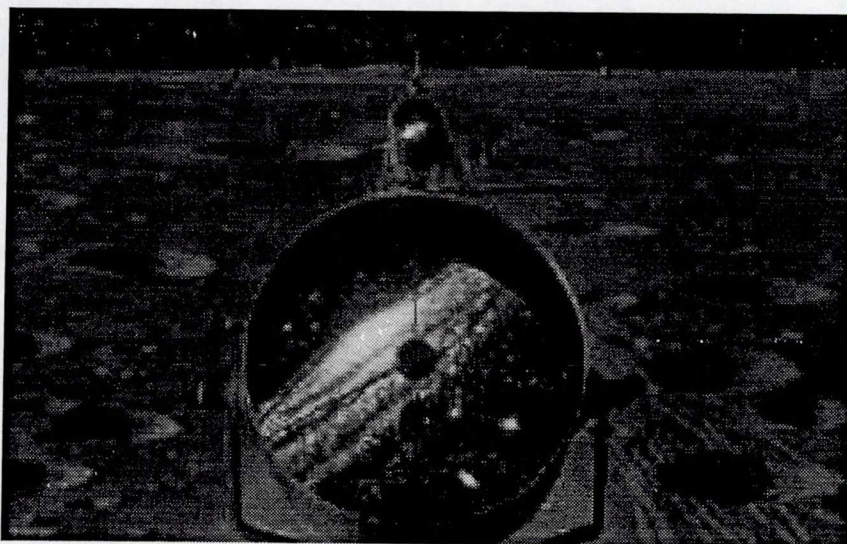


FIGURE 14: A complete array of large scientific observatories could be erected

Field expeditions using advanced ground transportation systems will become routine and will enable extended field expeditions to remote corners of the lunar surface. Missions will be conducted in a comfortable shirt-sleeve

environment that will serve as a habitat for rest and relaxation, as a radiation shelter from solar events, and as an emergency medical care facility for injured crew persons. With field laboratory equipment, these mobile surface outposts will serve as a meeting area and staging point for all extravehicular activities.

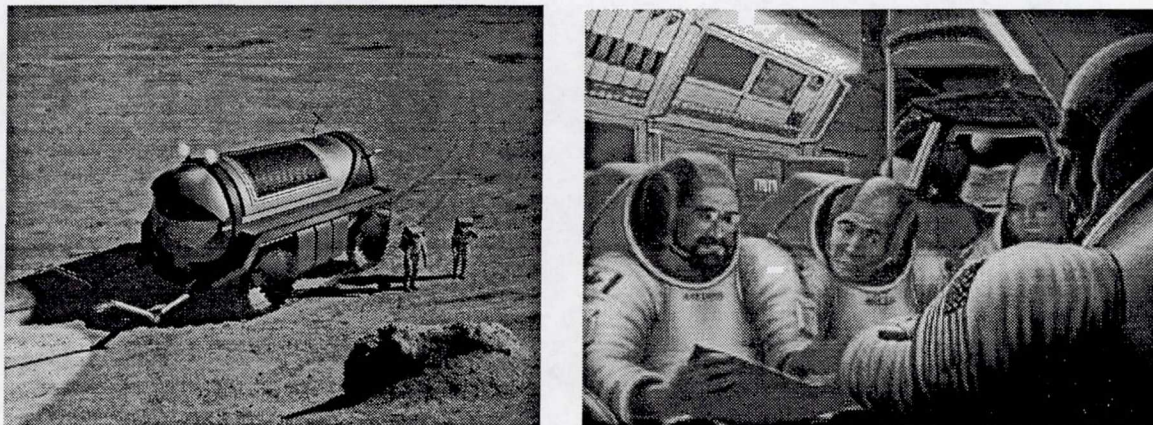


FIGURE 15: Advanced surface transportation will enable extended field expeditions for remote lunar surface access

These expeditions will allow lunar samples to be gathered and processed from a variety of surface locations including craters, plains, and highlands, lava tubes and other geologic features of interest. Finally, scientific instruments such as solar collectors and seismometers will be deployed and monitored from remote locations across the lunar surface.

During this period large-scale mining operations will developed as an integral part of the lunar economy. Mining operations will sustain the lives the colonists by providing air, water, and spacecraft propellants from the lunar soil and possibly from water-ice at the lunar poles. Metals mined from lunar mines including magnesium, titanium, chromium, iron, zinc, nickel, and cobalt, could provide building materials for structures, raw materials for manufacturing capability, and as raw material for export to Earth.

THE FUTURE

With the emplacement of mining operations, materials processing, manufacturing facilities, communications, media, and entertainment services, the stage will be set for the establishment service organizations, educational facilities, political institutions, and a full-scale economy. As the lunar outposts grow and mature, their surface infrastructures will correspondingly grow and become more complex. Outposts will be established across the lunar globe, and travel to and from the moon will become commonplace. Commerce between Earth and the Moon will develop and flourish; and as the human presence on the moon develops and matures, lunar outposts will become lunar bases—lunar bases will become lunar colonies—lunar colonies will become independent city-states or independent nations. The lunar population will become as diverse on the moon as it is on Earth with scientists and engineers of all disciplines, technicians, doctors, lawyers, teachers, and students, with representation from all races, and nationalities.



FIGURE 16: A full-scale lunar economy will develop as lunar colonies develop and mature into lunar states

Turner Entertainment © 1968

Advanced cities on the moon will be built with residential areas, business institutions, manufacturing facilities, utilities and communications infrastructures, houses of worship, spaceports—which serve as intra-lunar and interplanetary transportation nodes, parks and recreational facilities, and educational institutions. Life in these cities will, in many ways, resemble city life on Earth. Living conditions will improve dramatically with the development of comfortable residential housing. Parents will go to work and raise their children, and children will go to school, make friends, and do their home-work. There will be differences too. Basic resources such as air and water will be judiciously recycled in order to conserve critical life-sustaining commodities. City planners and local governments will be very conscious about the creation, processing, and disposal of wastes in order to maintain a healthy quality of life. Materials of all kinds will be recycled in order to reduce the amount of raw materials that must be imported from Earth. The farming industry will become crucial to the sustaining of life in the colonies, cities, to feed the people who live and work there. Living on the moon will never be quite the same as living on earth, but analogs will be created to improve the quality of life for its citizens.

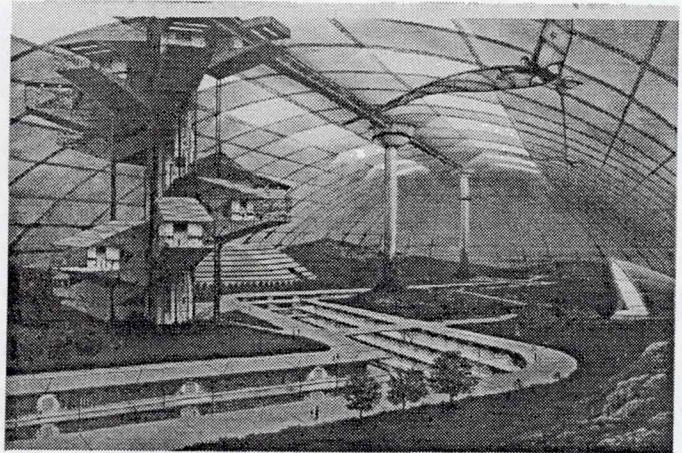
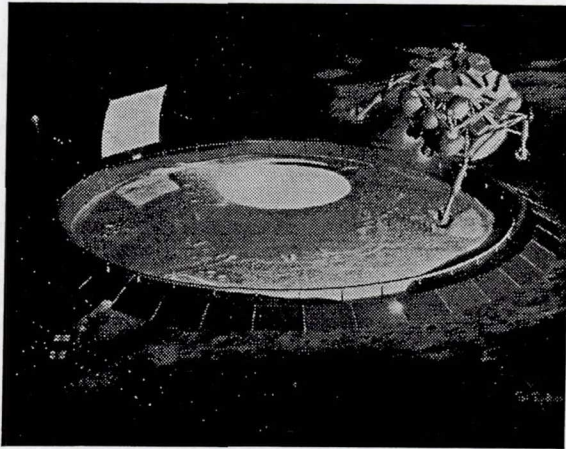


FIGURE 17: Advanced cities—both above and below ground, will be built to accommodate the lunar citizenry

Of course living on the moon will not be all work and no play. Recreation will take on new and novel forms. Many new sports will be invented that would not be feasible on earth due to its more powerful gravity field. Even in the restricted environment of lunar society, people will find safe and enjoyable outlets for fun and recreation. And of course, the moon will become a popular destination for Earth's tourists as well as for vacationing citizens who live on the moon. In fact, the lunar tourist business will help the local economies thrive and increase independence from Earth.

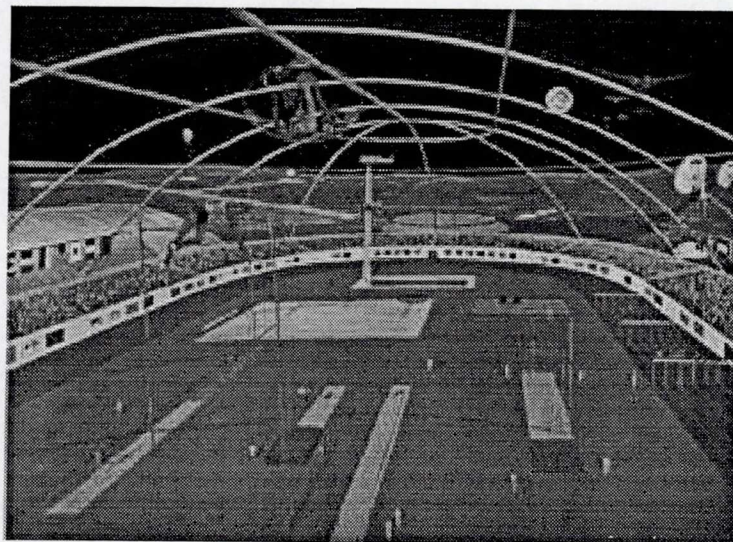


FIGURE 18: Domed stadium for spectator sports such as track and field

To summarize, humanity will return to the moon because it is the nearest celestial body to our home planet which avails itself to terrestrial political and economic expansion, because it offers opportunities to exploit new known reserves of natural resources through mining operations, and because it offers a new exotic destination for the tourist industry. It will also enable scientists to gain new knowledge about the universe through scientific study, and it will provide a providing ground for the development of enabling technologies for the development of space assets in support of missions to Mars and the outer planets.

But there are other reasons why humanity must expand its presence beyond the confines of the Earth. In the event of a disaster such as a comet or asteroid impact with the earth, global war, environmental degradation, or a medical epidemic, humans should have destinations of refuge in order to enable survival of the species and to perpetuate the knowledge and technological prowess that it has so painstakingly been developed over the centuries.

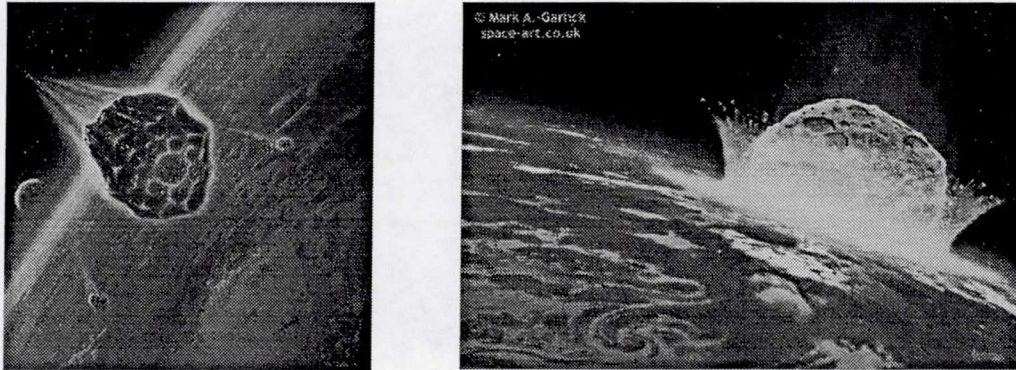


FIGURE 19: An asteroid or comet impact with the Earth could destroy life on our home planet as we know it today

On a more positive note, Konstantin F. Tsiokovsky the great Russian space pioneer of the early twentieth century stated the “the Earth is the cradle of the mind, but we cannot live forever in a cradle”. Our earth is one tiny planet among the what must be millions of inhabitable planets in our galaxy alone. Virtually limitless resources and opportunities beyond the boundaries of Earth, await those who are willing to accept the challenges and risks in obtaining them. Our species must push beyond the boundaries of Earth to avoid eventual cultural and economic stagnation. Finally, humans have a need to dream, explore, and discover new horizons, and to ‘boldly go where no one has gone before’. Space is indeed that final frontier. Ad astra per astra.

NOMENCLATURE

CTV – Crew Transfer Vehicle
EVA – Extra-Vehicular Activity
ISS – International Space Station
L1 – Lunar Lagrange point one
LRV – Lunar Roving Vehicle
NASA – National Aeronautics and Space Administration
Nav/Comm – Navigation/Communication
US – United States

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