Development of Self-Sustaining Mars Colonies Utilizing the North Polar Cap and the Martian Atmosphere

Final Report
NIAC Research Grant 07600-053

J. Powell, G. Maise, J. Paniagua, and J.R. Powell
Plus Ultra Technologies, Inc.
PO Box 547
Shoreham, NY 11786

November 20, 2000

SUMMARY

A revolutionary new concept for the early establishment of robust, self-sustaining Martian colonies is described. Instead of depending on transporting supplies to Mars from Earth, virtually all fuels, propellants, water, breathable air, construction materials, and food needed for the colony would be produced on Mars, using in-situ H_2O and the CO_2 Martian atmosphere.

A major objective of the NASA Mars exploration program has been to see if there are water sources that can serve as a raw material for the in-situ production of supplies.

However, there already is an immense body of known, readily accessible Martian H_2O that can support robust, self-sustaining colonies. Thousands of cubic kilometers of water ice exist in Mars' North Polar Cap, with local thicknesses of up to at least one kilometer.

By landing two compact, lightweight separate robotic factories close to each other on the surface of the North Polar Cap, a very large amount of propellants, fuels, air, water, construction materials, and food can be manufactured and stockpiled at the colony site before the astronauts depart from Earth to go to Mars. These materials would be ready for use when the astronauts arrived at the North Polar site.

Each robotic factory, termed ALPH (Atomic Liberation of Propellant and Habitat) utilizes a compact, lightweight nuclear reactor as its energy source. Two ALPH factories, each weighing on the order of 4 to 5 metric tons, would produce and stockpile

- 160 tons of liquid H_2
- 1608 tons of liquid O_2
- 60 tons of liquid CH_4
- 60 tons of methanol
- 30 tons of plastic
- 4 tons of food

The thermal rating of each ALPH reactor is ~2.7 megawatts(th). Each reactor produces 250/C, 37 atmosphere steam which generates electric power using a compact, light turbo-generator. The thermal efficiency of the ALPH power cycle is 20%, resulting in an electric generation of 540 KW(e) from each unit. Waste heat is rejected into the low temperature (-100/C) ice sheet. A major advantage of operating power sources on the Mars ice cap is the availability of an easily accessible, very cold heat sink. This greatly simplifies the power generation cycle, as compared to radiating waste heat away at much higher temperature, or convecting it to a very low density atmosphere. The reactor and power cycle systems used in ALPH are very conservative and well within the existing technology base.

Figure 1 shows an overall view of the ALPH system after it has landed on the ice cap surface and begun its deployment. Using reactor thermal heat, warm melt water lines carve out sub-surface channels and storage cavities. Electric power from the sub-surface reactor/turbo-generator unit is used by a small water electrolyzer on the lander to produce hydrogen and oxygen (Figure 2). Some of the H_2 and O_2 is liquefied and stored in insulated sub-surface cavities, while some is combined with atmospheric CO_2 in process units on the lander to produce and stockpile liquid methane, methanol, plastics (e.g., polyethylene) and food (e.g., high protein yeast and algae grown in small bioreactor units).

In addition to producing and stockpiling supplies, the ALPH factories would create a number of sub-surface, spacious cavities to serve as living and work quarters for the arriving astronauts. These quarters would be located at a sufficient depth (e.g., ~10 meters down) that the astronauts would be fully shielded from cosmic rays. The quarters would be thermally insulated and supplied with breathable air (21% O_2, 79% N_2 at a total pressure of 1 atmosphere) produced from electrolytic O_2 and atmospheric N_2.

Before selecting a site for the colony, a number of small, light weight robotic probes termed MICE (Mars Ice Cap Explorer) would be landed at promising sites on the North Polar Cap.

Using a small, light weight (~100 kg) nuclear reactor as its energy source, the MICE probe would travel for distances of kilometers under the ice cap (Figure 3) along melt channels created by its warm water jets. MICE would gather data on the internal structure (dust content, CO_2 content, layering, etc.) of the ice cap and the ancient geologic and meteorologic history of Mars atmosphere, dust, as well as searching for evidence of ancient life (microfossils, DNA traces, organic chemicals, etc). Data would be relayed from the probe to a lander via optical fiber, and transmitted back to Earth. Depending on the results from the various probes, a site for the Mars Colony would be chosen.

MICE and ALPH could be developed to support an initial landing of colonists at the colony site in 2018 AD. This colony could grow very rapidly, reaching a total population of approximately 500 people in the mid 2030's.

The first two key elements in establishing a robust Mars Colony are the development of MICE and ALPH. These systems utilize well established technology, and could be fully tested and demonstrated on Earth ice sheets (e.g., in Greenland, Antarctica, etc.) before being sent to Mars.

The second two key elements in establishing a robust Mars Colony are the development of a compact, light weight nuclear thermal propulsion system, and an Earth-Mars-Earth transport architecture that utilizes propellant manufactured on Mars to make round trips between Earth and Mars.

A compact nuclear thermal propulsion engine, termed MITEE (MIInature ReacTor EnginE) is described (Figure 4). MITEE is based on an adaptation of an extensive body of nuclear engine technology developed in the 1950's through the 1990's in the US and USSR. Using H_2 propellant, MITEE can achieve a specific impulse of ~1000 seconds, over twice that of the best chemical propulsion (i.e., H_2 /O_2) engines, while having a small mass (~150 kg) and a high thrust/weight ratio (~15/1).

Because of its extensive technology base, MITEE could be developed relatively quickly, i.e., in ~5 to 6 years. Availability of the MITEE engine would provide a quantum jump in planetary science exploration capability, in that it would greatly reduce mission travel time (e.g., only 2 years to Jupiter and 5 years to Pluto), mission launch cost (substantially smaller launch vehicles), and enable important new and unique missions (e.g., Pluto orbiter, Europa sample return, Jupiter or Saturn atmospheric flyer; Pluto sample return, etc.).

Implementation of MITE for such planetary science missions would help to speed up the development of a robust Mars Colony, through the ability of MITEE to transport colonists in a short trip time (e.g., 3 months), and to deliver cargo with reduced IMLEO requirements.

The fourth key element in establishing a robust Mars Colony is the ability to manufacture H_2 propellant at the colony site and transport it to a propellant depot in Mars orbit with relatively low)V requirements. From there, a portion of the H_2 propellant would be transported back to a second propellant depot in GEO orbit above Earth, also with relatively low)V requirements. Figure 5 shows the architecture for passenger round trips between Earth and Mars. A similar architecture is used for propellant transport from Mars surface to GEO orbit.

The launch benefits of manufacturing colony supplies and propellant on Mars and transporting it from Earth to Mars are shown in Figure 6. Using propellant manufactured on Mars and transported to GEO colonists can make round trips between Earth and Mars possible with a launch capability, Earth surface to LEO, of only 8 tons per person. As illustrated in Figure 6, this IMLEO is a factor of ~10 less per person than the present approach in which most of the propellants and supplies needed for a Mars mission are launched from Earth. The much smaller IMLEO requirements possible with the colony approach translate into substantially reduced costs for a Mars exploration program.

To illustrate the potential exploration capabilities, quality of life, and production requirements a point design for a 500 person Mars Colony based on the ALPH concept was investigated. This colony termed Xanadu [after Coleridge's poem "Kubla Khan"] could be in place by approximately 2040 AD, if there were a vigorous development effort on ALPH and a high performance propulsion system, such as MITEE, and a commitment to establishing the Mars Colony.

Figure 7 shows the quality of life that could be achieved in Xanadu using ALPH robotic factories. Colonists would have virtually unlimited quantities of water, breathable air, and food, and would live in spacious, warm, shirt sleeve type habitats located under the surface of the ice sheet, where they would be fully shielded from cosmic rays. The colonists would have excellent medical care, since the colony is large enough to have a wide range of medical specialists and equipment.

The exploration capabilities of the Colony would be far greater than could be carried out by conventional missions launched from Earth. Figure 8 shows the various modes of possible exploration. Manned land rovers based at the Colony could explore the North Polar Cap and surrounding terrain at distances up to ~1000 kilometers, and return large amounts of samples to the colony. Longer range exploration would be performed using unmanned and manned flyers. Sites as far away as the South Pole could be visited, to obtain data on local geology and collect samples for return to the colony.

Fuel, e.g., methane/oxygen, and supplies for the manned rovers would be produced at the colony. The unmanned flyers would be powered by an on-board compact, light weight reactor that would heat atmospheric CO_2 for propulsion. The manned flyers would be powered by on-board, methane/oxygen combustion source that would heat atmospheric CO_2 for propulsion. To achieve long flight distances, the manned flyers would refuel with methane/oxygen deposited by the unmanned flyers at various depots established on Mars.

Not only would the fuel and other supplies (food, water, etc) needed for the above exploration journeys be produced at the Colony, but the rover and flyer vehicles themselves would be fabricated at the Colony, using materials (plastics, composites, etc) manufactured by the Colony.

The unmanned flyers could visit hundreds of sites on Mars each year and return tons of samples to the Colony for analysis. The manned rovers and manned flyers would each make on the order of a dozen journeys per year, with tens of sites visited on each journey.

The total reactor power needed to comfortably sustain a colony of 500 persons on Mars is modest, only about 60 megawatts thermal. With a 20% thermal cycle efficiency, the electric power generated is 12 megawatts (e). This generation would be provided by 6 individual ALPH reactors, to ensure system reliability.

Table 1 outlines the amounts of principal materials produced each year by the ALPH system. These materials not only include ample supplies for life support and Mars exploration, but also the propellant for round trips between Earth and Mars. The number of round trips will depend on the fraction of colonists that want to return to Earth at a given synodic cycle. For purposes of estimating propellant production requirements, a return rate of 20% of the Colony's population every 2 years is assumed.

Substantial technology developments will be required to have the capability to establish a Mars Colony. These include:

1. A small nuclear reactor that would produce hot water and/or steam for melting cavities in ice sheets, as well as generating electricity using a small steam turbine. This reactor could be used in both the MICE probes and the ALPH factories.
2. Compact light weight process units that can: a) electrolyze water, b) liquefy H_2, O_2, and methane, c) combine CO_2 and H_2 to produce methane, methanol, and plastics, and d) produce algae and yeast based foods.

3. A compact, light weight nuclear thermal propulsion engine, such as the MITEE concept, that can achieve high specific impulse (e.g., ~1000 seconds) and high thrust to weight ratios.
4. A new class of spacecraft that can: a) transport passengers to and from Mars, b) transport cargo to and from Earth orbit to Mars orbit, c) transport propellant from the surface of Mars to Mars orbit, and d) orbital propellant depots based on spent shuttle tanks.

There already exists an extensive technology base with respect to the first 3 areas. Based on this technology base and the conservative performance parameters, e.g., the power cycle efficiency is only 20%, considerably less than that routinely achieved in conventional steam power systems. These items could be developed in 5 to 6 years, given a vigorous R&D program. Moreover, the developed MICE and ALPH systems could be tested on Earth ice sheets, and a developed MITEE engine could be implemented and ready for major planetary science missions by 2010. The development cost of these systems appears to be modest, amounting to a total of several billion dollars.

The critical technology path for establishing a Mars colony does not appear to be with the first 3 items, but rather with the development of the spacecraft needed for the Earth-Mars-Earth transport architecture. The R&D for these spacecraft will account for the majority of the development cost, and will take the most time to achieve.

The first 2 spacecraft - that is, the craft needed to transport passengers and cargo - would also have to be developed for the conventional type of manned Mars mission, where all of the supplies would be brought from Earth.

The last 2 spacecraft are new and specific to the Mars colony concept. These are the fueling shuttle and the shuttle tanks used for the propellant depots. These appear to be less of a development task than the first 2 spacecraft.

With a vigorous well funded development program it should be possible to have these spacecraft ready for use by approximately 2020.

It is concluded that the Mars colony concept presented here is technically practical, and could be implemented at a cost that would be comparable to that for a conventional Mars exploration approach. The colony approach would enable a much greater exploration capability, with hundreds of sites visited annually, instead of one or two every few years, and with tons of samples returned for analysis, rather than a few kilograms.

Moreover, the colony approach would greatly reduce risk to the explorers, and greatly increase their ability to function effectively, through the reduced physical and mental stresses they would experience.

Figure 1

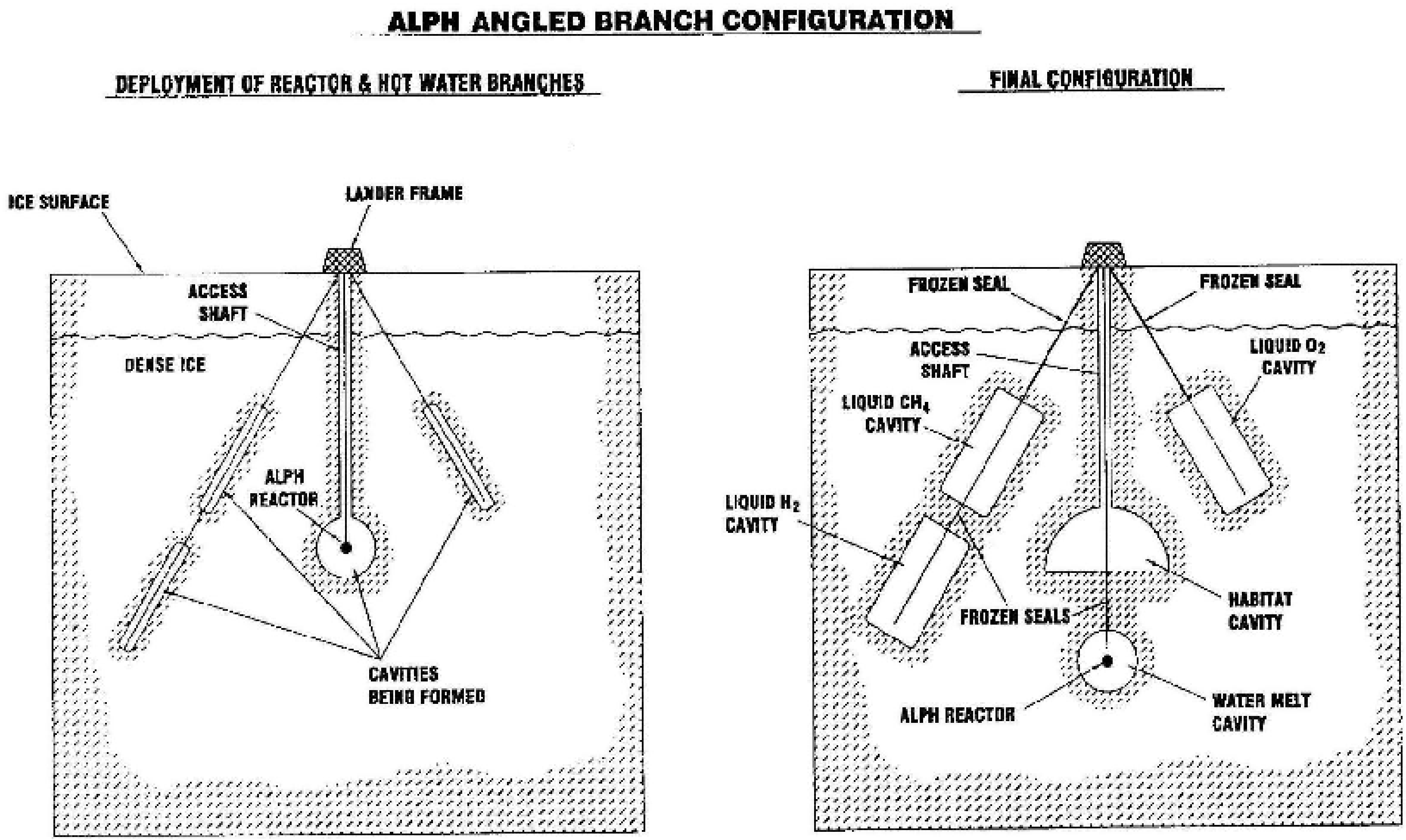

ALPH ANGLED BRANCH CONFIGURATION
DEPLOYMENT OF REACTOR & HOT WATER BRANCHES
ICE SURFACE
LANDER FRAME
ACCESS SHAFT
DENSE ICE
ALPH REACTOR
CAVITIES BEING FORMED
FINAL CONFIGURATION
FROZEN SEAL
FROZEN SEAL
ACCESS SHAFT
LIQUID O2 CAVITY
LIQUID CH4 CAVITY
LIQUID H2 CAVITY
FROZEN SEALS
HABITAT CAVITY
ALPH REACTOR
WATER MELT CAVITY

Figure 2

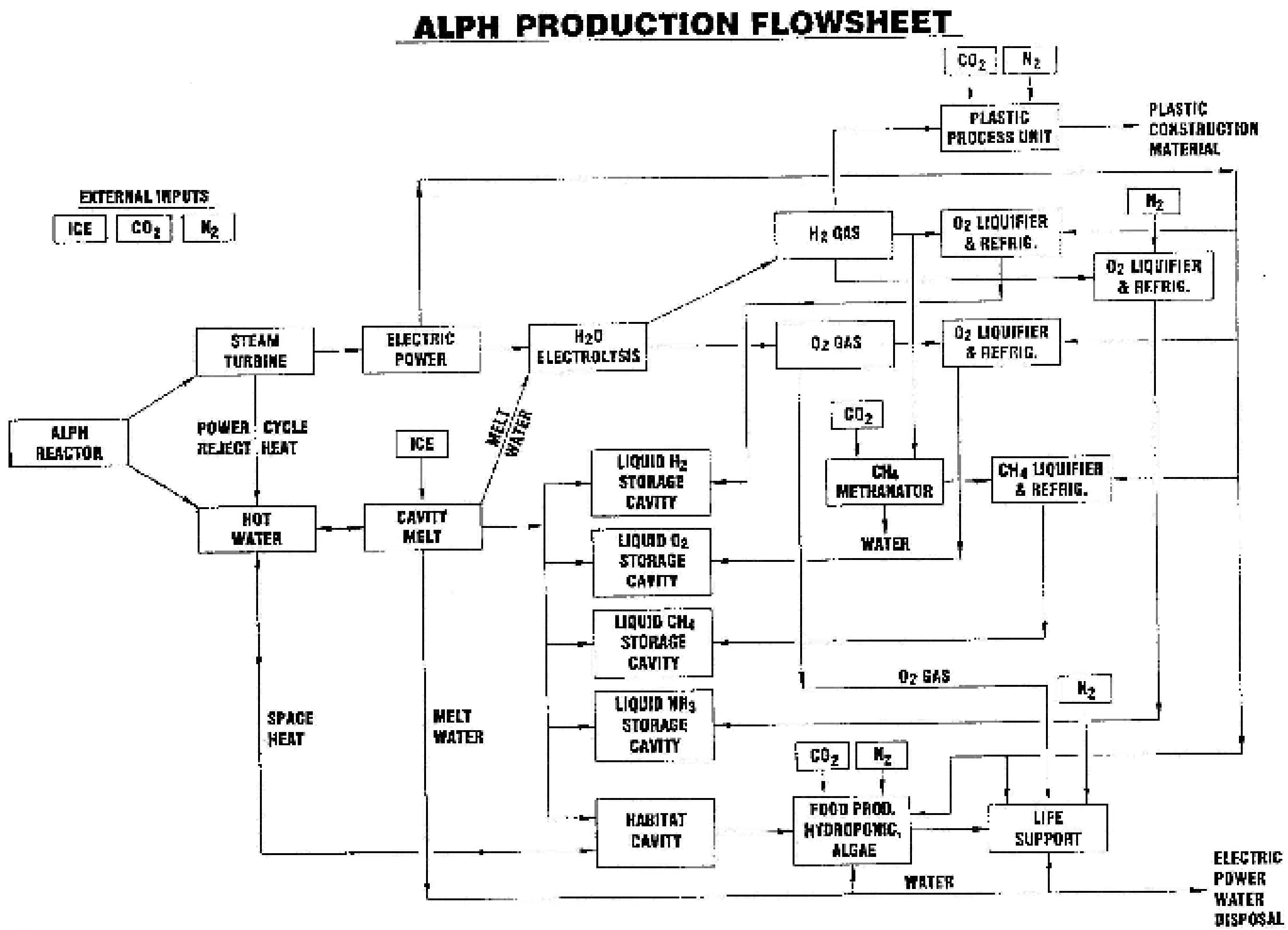

ALPH PRODUCTION FLOWSHEET
EXTERNAL INPUTS
ICE
CO_2
N_2
ALPH REACTOR
STEAM TURBINE
POWER CYCLE REJECT HEAT
HOT WATER
ELECTRIC POWER
ICE
CAVITY MELT
MELT WATER
H_2O ELECTROLYSIS
H_2 GAS
O_2 GAS
O_2 LIQUIFIER & REFRIG.
O_2 LIQUIFIER & REFRIG.
O_2 LIQUIFIER & REFRIG.
N_2
CO_2
N_2
PLASTIC PROCESS UNIT
PLASTIC CONSTRUCTION MATERIAL
CO_2
CH_4 METHANATOR
WATER
CH_4 LIQUIFIER & REFRIG.
LIQUID H_2 STORAGE CAVITY
LIQUID O_2 STORAGE CAVITY
LIQUID CH_4 STORAGE CAVITY
LIQUID NH_3 STORAGE CAVITY
HABITAT CAVITY
O_2 GAS
N_2
CO_2
N_2
FOOD PROD. HYDROPONIC, ALGAE
LIFE SUPPORT
WATER
SPACE HEAT
MELT WATER
ELECTRIC POWER WATER DISPOSAL

Figure 3

The MICE (Mars Ice Cap Explorer) Concept

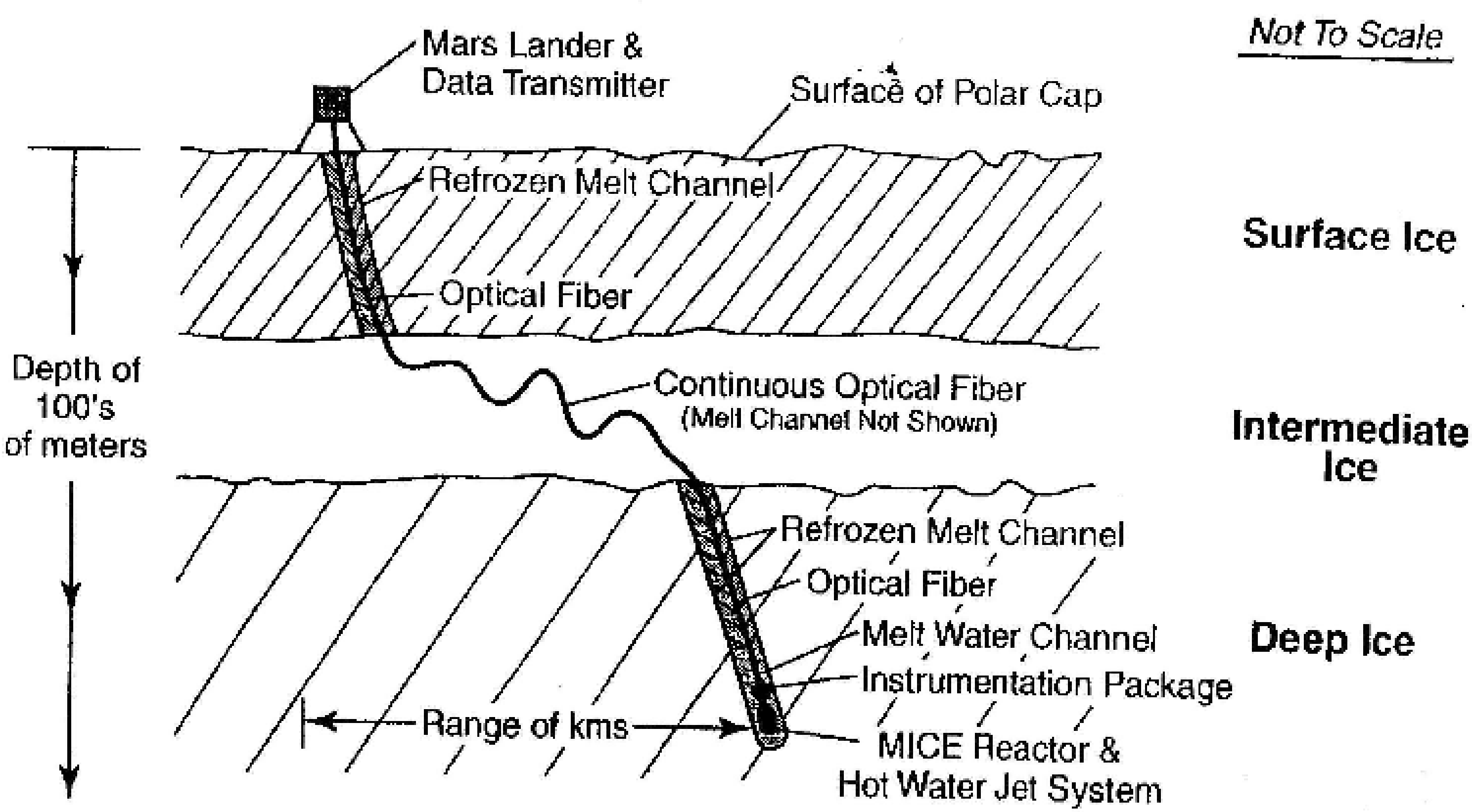
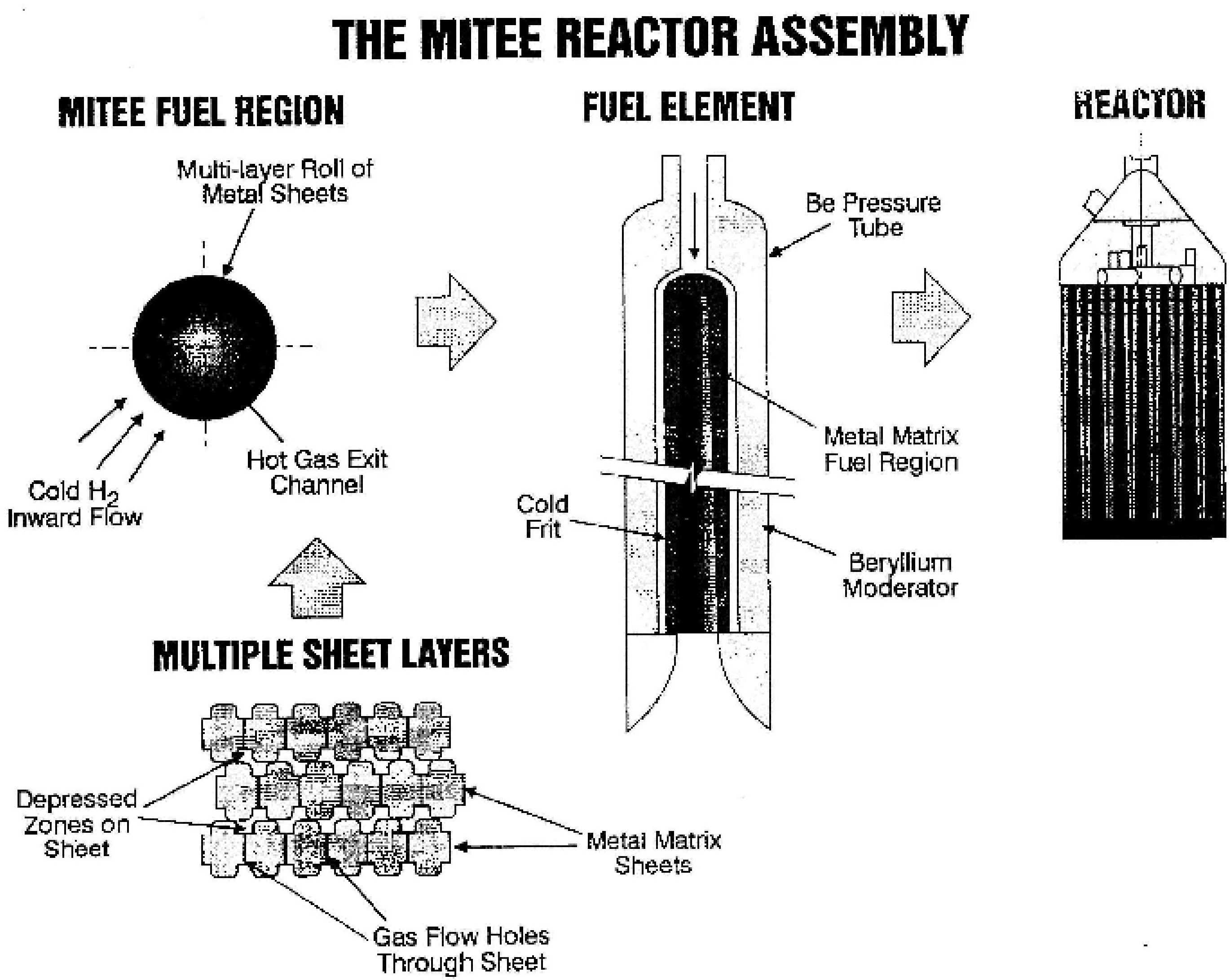


Figure 4



THE MITEE REACTOR ASSEMBLY
MITEE FUEL REGION
Multi-layer Roll of Metal Sheets
Cold H2 Inward Flow
Hot Gas Exit Channel
FUEL ELEMENT
Be Pressure Tube
Metal Matrix Fuel Region
Cold Frit
Beryllium Moderator
REACTOR
MULTIPLE SHEET LAYERS
Depressed Zones on Sheet
Metal Matrix Sheets
Gas Flow Holes Through Sheet

Figure 5

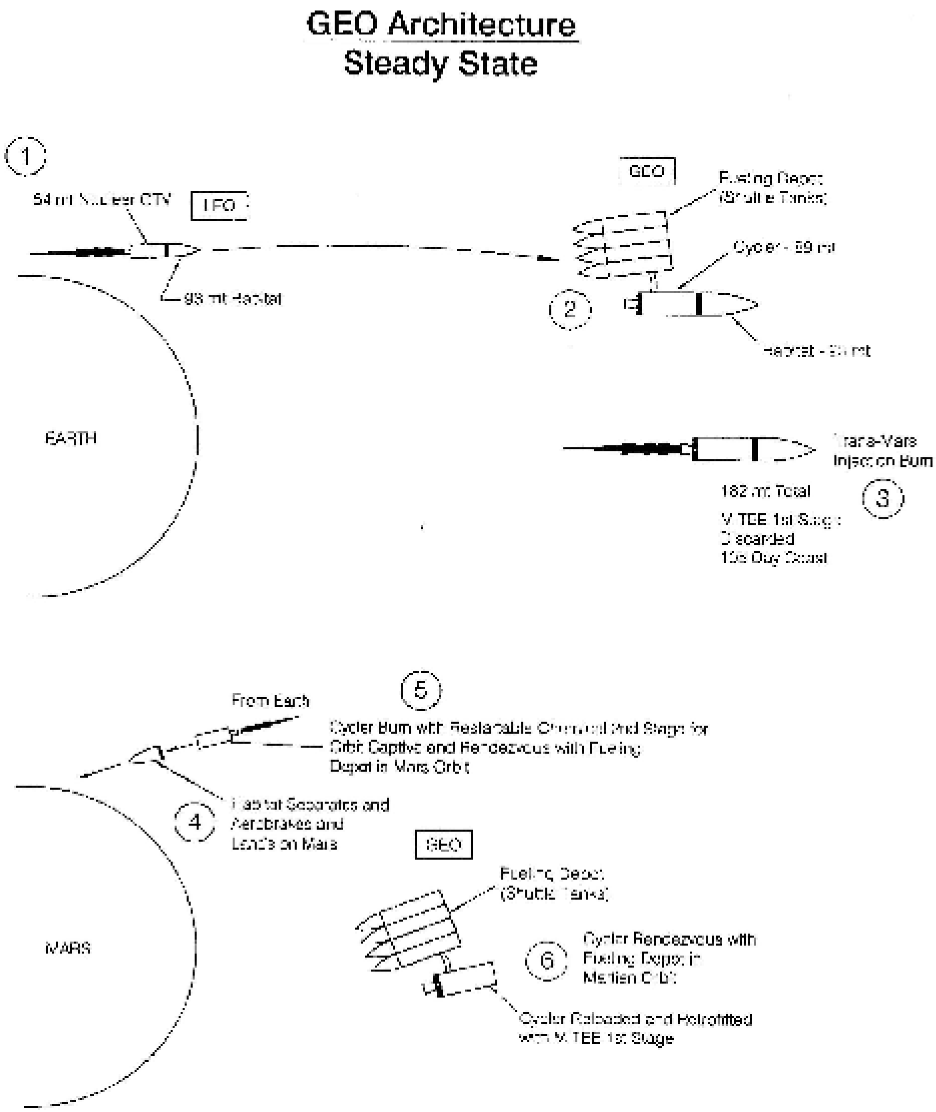

GEO Architecture
Steady State
1
GEO
EARTH
2
182 mt Total
3
5
From Earth
4
GEO
MARS
6

Figure 6

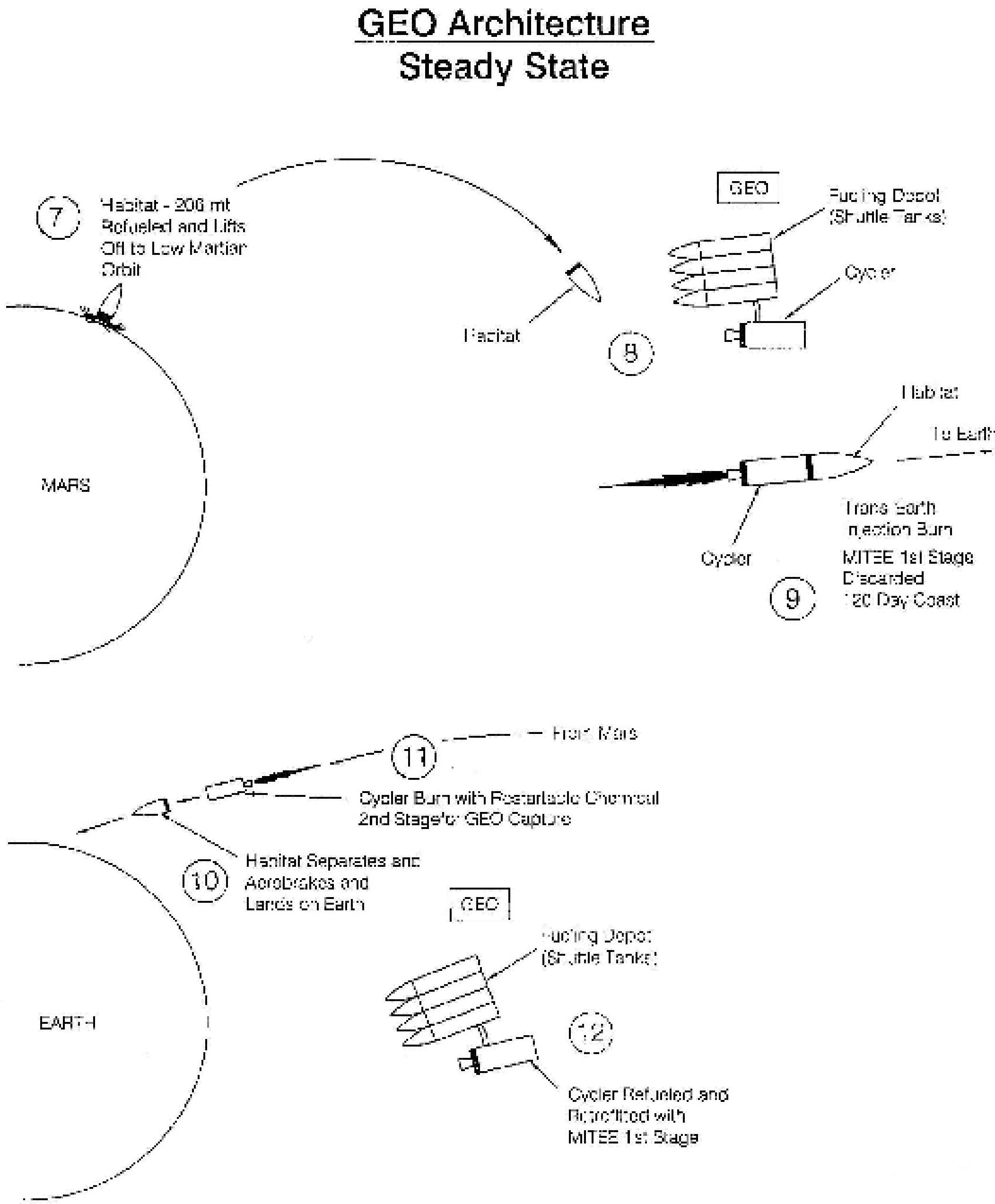

GEO Architecture
Steady State
7
Habitat
Refueled and Lifts
Off to Low Martian
Orbit
MARS
GEO
(Shuttle Tanks)
Cycler
Habitat
8
Habitat
To Earth
Cycler
MITEE 1st Stage
Discarded
120 Day Coast
9
From Mars
11
Cycler Burn with Restartable Chemical
2nd Stage for GEO Capture
Habitat Separates and
Aerobrakes and
Lands on Earth
10
EARTH
GEO
(Shuttle Tanks)
12
Cycler Refueled and
MITEE 1st Stage

Figure 7

Earth To Orbit Launch Mass Required To Transport A Colonist and Supplemental Supplies To Mars

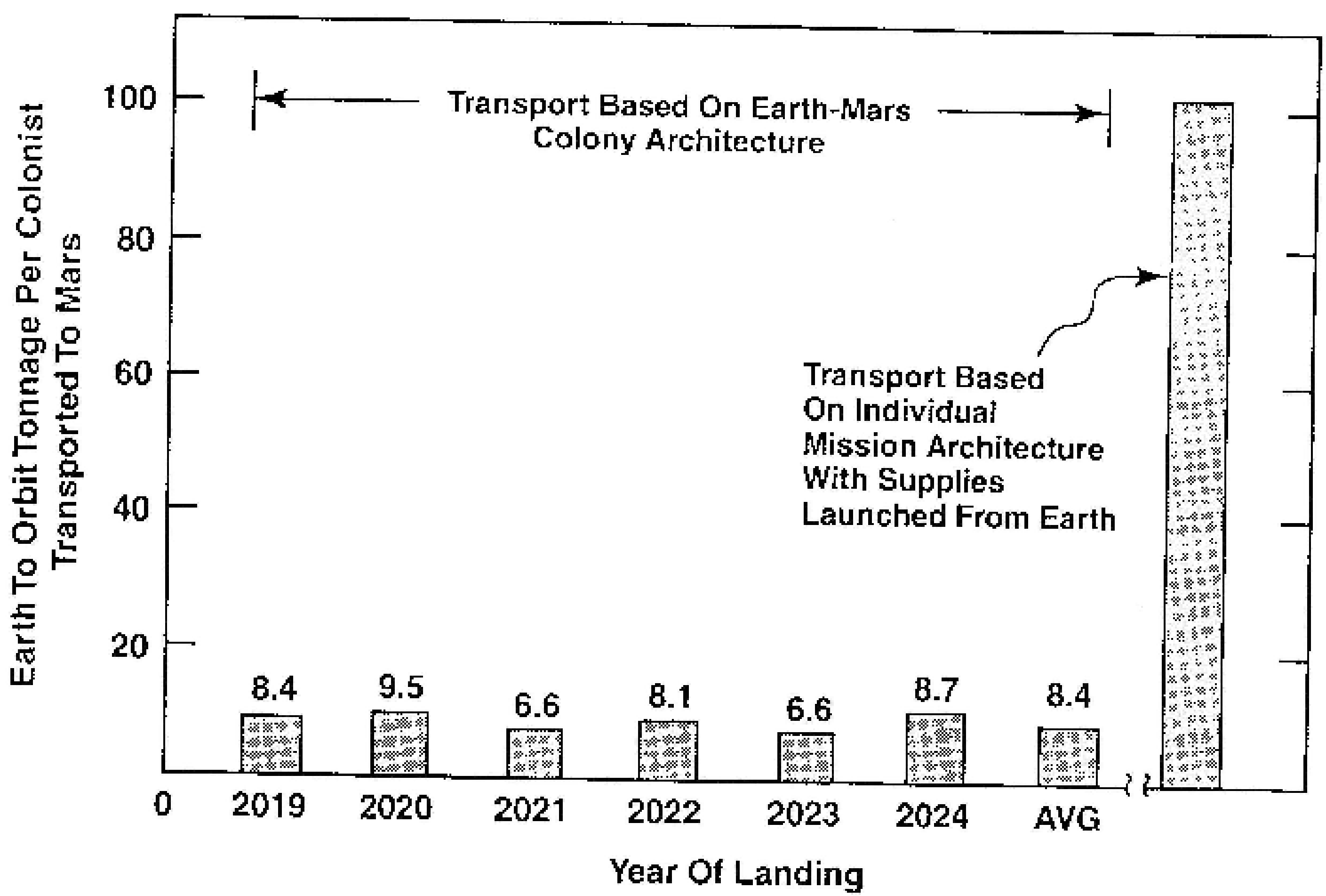


Figure 7

An Excellent Quality of Life in Xanadu is Possible

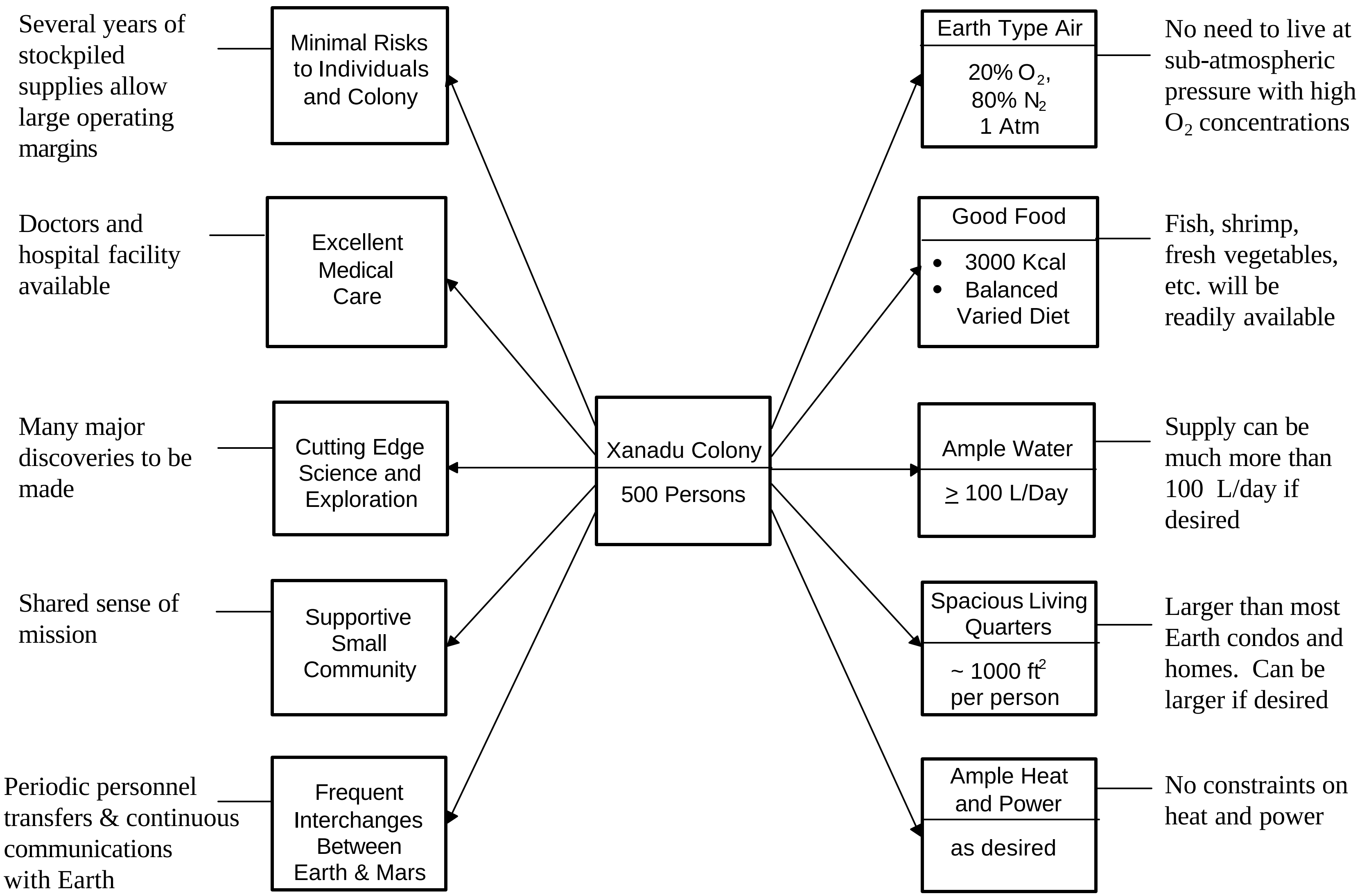


Figure 8

Exploration Modes for Xanadu

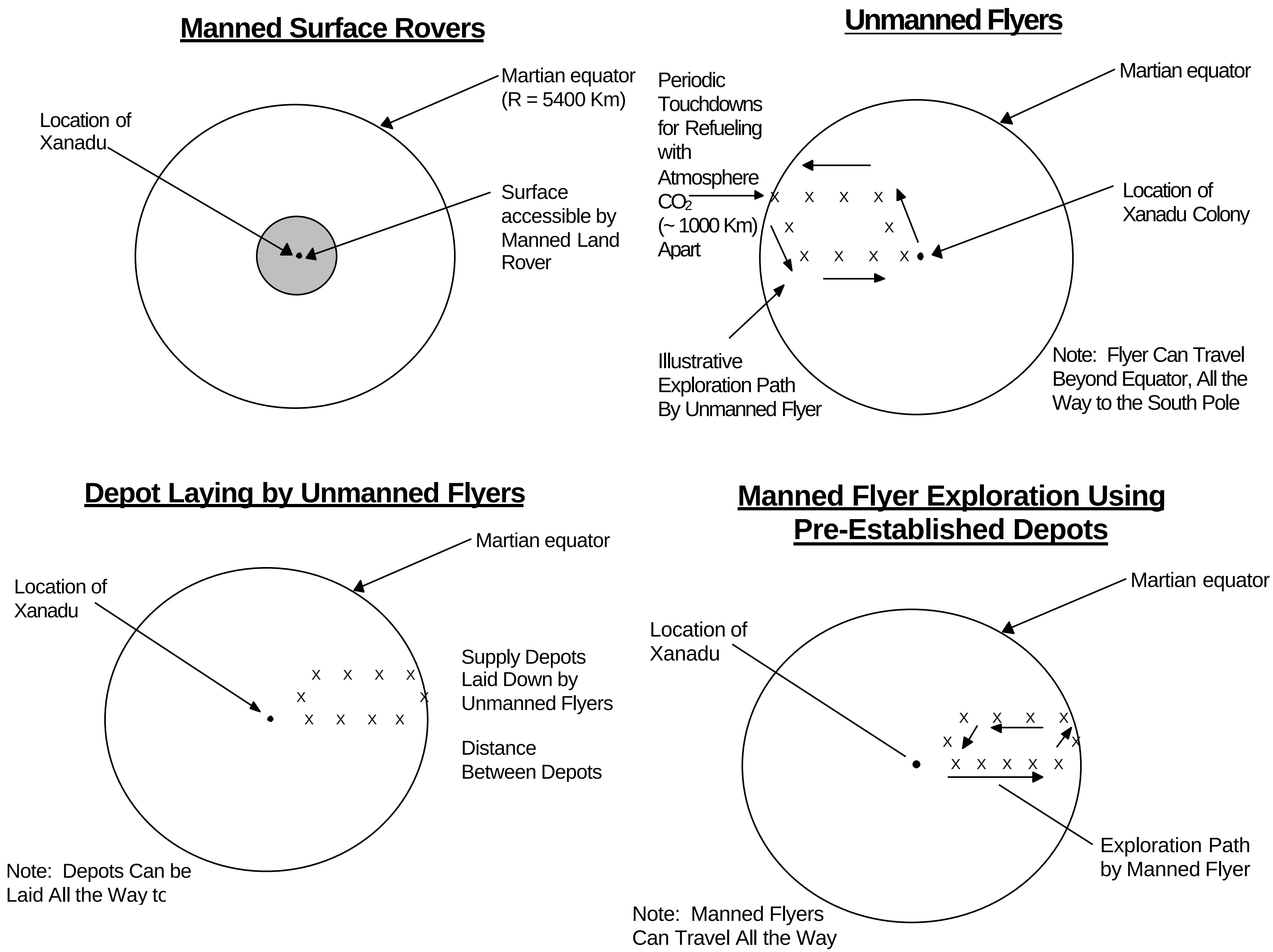


Table 1 ALPH Production Rate for Xanadu Colony

Basis: Average yearly production rate | Steady state colony of 500 persons | 20% turnover every 2 years

Total reactor thermal power		60 MW (th)
Total electric generation		12 MW (e)
Number of ALPH reactors (10 MW[th])		6
H_2 production, metric tons per year		
Liquid H_2 for Earth-Mars-Earth transport		835
H_2 for CH_4 and CH_3OH fuel		40
H_2 for plastics		80
H_2 for food substrates		90
H_2 for stockpile (30%)		300
	Total	1345
O_2 production, Metric tons per year		
Liquid O_2 for Earth-Mars-Earth transport		1430
O_2 for breathable air		80
O_2 for combustible fuels		800
O_2 for plastics and food		100
O_2 for stockpile (50%)		1200
O_2 surplus (discarded)		8500
	Total used	3610
General supplies, metric tons per year		
Breathable air (80% N_2, 20% O_2)		400
Water for life support		18,000
CH_4 for exploration		15
Fuels for colony		180
Plastics		500
Food (including 50% stockpile)		270
Electric power for life support		2 MW(e)
Space heat for life support		12 MW(th)

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF TABLES

1 INTRODUCTION

Studies of the initial stages of the manned exploration of Mars have tended to concentrate on the "multiple mission approach," as illustrated in Figure 1.1. Individual missions depart from Earth to land at a specific Mars site, exploring it for a short or long period - 30 days or one and a half years, depending on whether it is an opposition or conjunction class mission. Each individual mission explores a different site, with the starting point always being Earth.

The exploration of Mars, at least in its initial stages, is thus a long drawn out process involving a sequence of individual missions, each of which has to carry from Earth almost all of the supplies that it needs for a trip to Mars, the exploration itself, and the return trip to Earth. As Zubrin (1) and others have proposed, certain supplies can be produced on Mars (e.g., methane and oxygen from atmospheric CO_2, using hydrogen transported from Earth). However, the amount of supplies thus produced is modest, and does not yield a major reduction in expedition requirements.

Each mission requires lifting at least 500 metric tons into Low Earth Orbit (LEO). Moreover, mission capabilities are constrained, and mission risks increased, by the drive to minimize mission cost and launch requirements. This inevitably drives down margins on the amounts of propellants, consumables, etc. that are carried, decreases operating margins on equipment, and so on.

In the past on Earth, exploration has been the most rapid and successful when explorers have established continuously occupied bases on the new lands, and have used local resources for the bulk of their activities. The same pattern would appear to apply to Mars.

Clearly, if Mars were a habitable and hospitable world, such a pattern of exploration would be followed there. However, the absence of breathable air and water has seemed to prevent this. There has been great interest and speculation about whether or not there is water on Mars, and if so, whether it can be used to support habitats. Curiously, this fascination with finding water has virtually ignored the fact that thousands of cubic kilometers of ice are present in the North Polar regions, and readily accessible to support a colony.

Figure 1.2 outlines a different exploration approach, based on the establishment of a robust, continuously staffed colony located on the North Polar Cap of Mars. In contrast to the multiple mission approach, the colony would be established at the beginning of the exploration of Mars, not at some point in time that occurred long after a number of individual missions. A compact, lightweight robotic factory unit would land on the North Polar Cap at the site of the future colony site. The robotic unit, termed ALPH (Atomic Liberation of Propellant and Habitat) would produce and stockpile essentially all of the supplies (air, water, food, fuel, etc.) plus a large reserve margin, needed for the establishment and operation of the colony before the colonists arrived. The ALPH unit would also create large cavities under the surface of the ice cap that would provide comfortable, shielded habitats for the colonists.

All of the supplies and living space would be in place when the colonists arrived, ready for use. From the stockpiled materials, the colonists would construct rovers and flyers to carry out a large scale manned and unmanned exploration of Mars. All portions of Mars surface would be readily reached from the North Polar colony, including as far away as the South Polar region. Propellants and supplies would be lifted into Mars orbit and stockpiled in a depot for return trips to Earth. Moreover, additional propellant and supplies would be transported back to a depot in high Earth orbit, to be used for outbound trips to Mars.

The above concept for a Earth - Mars - Earth transport architecture, plus the production on Mars of virtually of the colony's material needs, would enable the colony to rapidly buildup to a level of hundreds of persons with minimum IMLEO launch requirements, as compared to the multiple mission approach. This advantage, plus the much greater exploration capability, make the colony approach extremely attractive for the initial stage of Mars exploration.

References:

1. Zubrin, R., The Case for Mars, Simon and Schuster, New York (1996).

2 DESCRIPTION OF THE NORTH POLAR COLONY CONCEPT

Figure 2.1 illustrates the advantages of the North Polar Cap as the base for a Mars colony. First, and most important, there is a plentiful supply of readily accessible H_2O locked up as ice. Water is the essential ingredient for a practical Mars colony. Without it, there could be no colony, and Mars would remain a dead world, visited occasionally by small exploration missions from Earth. With it, and the Martian CO_2 atmosphere, virtually all of the materials needed to comfortably support a major colony can be synthesized.

Moreover, what at first sight appears to be a drawback - the presence of H_2O as an ice sheet, rather than as underground water - is a major advantage. It enables robotic units to land and process H_2O from the ice into materials that can be easily stored in melt cavities created under the surface, as well as shielded habitats for the colonists when they land. Having the supplies and habitats already in place when the colonists land, rather then having to make them after they land, is a tremendous advantage. It decreases mission risk, since the colonists will not leave Earth until they know that the supplies and habitats are in place, and it greatly reduces the work demands on the colonists when they land, enabling them to concentrate on exploration.

In an odd way, Mars is a mirror image of Earth. On Earth, the vast ice sheets of Antarctica and Greenland, and the pack ice of the Arctic Ocean, are deserts, with the fertile continents being the oases. It is no wonder that these ice deserts were the last places on Earth to be explored.

On Mars, however, the North Polar Cap is the oasis, and the surrounding regions of the planet are its deserts. Logically, it appears wiser to explore the deserts from a robust, capable base located in the oasis, than attempting to set up camps in the inhospitable deserts. Moreover, as illustrated in Figure 2, the North Polar Cap appears to be a very attractive site for scientific research by itself. Samples obtained from inside the ice sheet will provide data on the composition and meteorology of the Martian atmosphere over millions of years, on the geology of the wind borne dust collected by the ice cap, on ancient solar wind and cosmic ray activity, and possibly, evidence of life on Mars, through microfossils, DNA traces, etc.

The key technology elements needed to achieve a successful colony on the North Polar Cap are summarized in Figure 2.2. First, more detailed information on the internal structure of the ice cap, and of possible landing sites, is needed. There appears to be a relatively small region of pure H_2O ice in the cap. This region, estimated to be 837 km^2 in area and at least 1 km thick (1), is surrounded by hundreds of thousands of square kilometers of layered polar terrain. Eroded channels in this region exhibit an internal structure of alternating layers of ice and dust. Typically, the ice layers are on the order of 10 to 30 meters thick, and are separated by thinner layers of dusty material, probably an ice-dust composite.

Quantitative data on the dust content in this portion of the Ice Cap, both locally and overall, is lacking. Carr (2) assumes for purposes of estimating the total inventory of H_2O on Mars that the average dust/ice content is 50%/50%. However, visual indications suggest that the dust content is substantially less than 50%; also, there probably is considerable spatial variation, since one would expect that the more northerly regions would have a smaller dust content, since most of the dust would have been trapped out at lower latitudes.

In general, having a dusty ice cap rather than a pure ice one would not pose any serious problems for the colony, as long as it did not hinder access to or processing the ice. Dust contents as high as 20 to 30% by volume would not appear to be a problem, since melt channels and cavities could still be created inside the ice sheet. The dust would be filtered or centrifuged out, and the purified water then used to make propellants, food, oxygen, etc.

The presence of dust in the ice cap would actually be beneficial, since it would be used as a feed material for processes to make aluminum, iron, and other metals, as well as ceramics based on silica, magnesia, etc. This would eliminate the need to make long trips to collect such feed material from sites at lower latitudes.

By landing compact, ultra lightweight mobile robotic devices on the ice cap prior to the establishment of the colony, one would be able to gather detailed data on the internal structure of the cap, including the content and composition of the dust, and how it varied vertically and horizontally within the cap. The small robotic devices, termed MICE (Mars Ice Cap Explorer), would travel vertically and horizontally through melt channels inside the ice cap, collecting data that would be transmitted back to Earth. Details of the MICE probes are described later.

The second key technology element is a compact, lightweight robotic factory unit that would land at the colony site two years before the first colonists arrived. The robotic factory unit, termed ALPH (Atomic Liberation of Propellant and Habitat) incorporates a small lightweight nuclear reactor that generates heat and electric power, together with a number of small process vessels that produce the desired supplies for the colony, using melt H_2O from the ice cap, CO_2 and N_2 from Martian atmosphere, and electric power from the reactor. The processes include water electrolysis to produce H_2 and O_2, methanation to produce CH_4 and CH_3OH, polymerization to produce polyethylene and other plastics, food production by yeasts and bacteria using CH_4 or CH_3OH substrates, and liquefiers to produce and store liquid H_2, O_2, and CH_4.

The third key technology element is a compact lightweight nuclear thermal propulsion (NTP) engine for transport back and forth between Earth orbit and Mars orbit. Using H_2 propellant, NTP engines can achieve specific impulses of about 1000 seconds, over twice that of the best H_2/O_2 chemical engines, which deliver only 450 seconds. The higher specific impulse performance of NTP engines greatly reduces the mass of propellant needed for transport between Earth and Mars, as compared to chemical engines. The chemical engines would be used for trips from planetary surface to orbit, both on Earth and Mars.

Over the past 50 years, there has been very extensive R&D on nuclear thermal propulsion engines in the US and the USSR. In the US, successful ground tests of complete NERVA NTP engines were carried out in the 1960's (3) successful tests of portions of NERVA type engines were also carried out in the USSR - up to the 1980's. The NERVA engine, however, was inherently large and massive, with power densities of only a few megawatts per liter, and a mass of several tons.

In the mid 1980's, the US initiated the SNTP program, which aimed at the development of a much smaller and lighter NTP engine based on the Particle Bed Reactor (PBR) for defense applications (4). Goals for the 1000 megawatt PBR NTP engine were a total mass of ~500 kilograms, with a thrust to weight ratio of 30/1. The components of the PBR engine were developed and successfully tested at the anticipated operational conditions. Ground tests of complete engine assemblies were planned but not carried out, due to the ending of the SNTP program at the close of the Cold War.

More recently, even smaller and lighter NTP engine designs have been studied for space exploration missions. In particular, the MInature ReacTor EnginE (MITEE) NTP engine mass is projected to be approximately 200 kilograms, with an outer diameter of the 75 megawatt reactor being only 50 centimeters. The MITEE engine, which uses the existing strong technology base on nuclear thermal propulsion, could be developed and applied to space exploration in as little as 5 years, given a strong development program.

The fourth key technology element for a practical Mars colony is an Earth - Mars - Earth transport architecture that minimizes the amount of material that has to be launched into orbit from Earth. An architecture that achieves this goal is described in detail later. As illustrated in Figure 2.2, a key element of this architecture is the establishment of propellant depots in Mars and high Earth orbit, i.e., at GEO or beyond. Using propellant transported from Mars orbit, spacecraft can travel back and forth between Earth and Mars without having to lift propellant from Earth for the trips. This, plus the ability to manufacture essentially all of the supplies used by the colony from Martian raw materials, reduces the Earth launch requirements to be just those needed to life colonists from Earth's surface to Earth orbit without having to also lift propellant and supplies for the trip to Mars and the return from it.

Figure 2.3 illustrates a possible road map for the establishment of the Mars colony. The first ALPH unit would land in 2016, manufacturing and stockpiling supplies for the first colonists, who would land in 2018. The initial landing party would consist of 10 astronauts. Additional groups of colonists would land continue to land at intervals determined by the Earth to Mars launch windows.

The colony would attain a mature population of 500 persons by 2034, sixteens years after the first human landing. A net return to Earth of approximately 20% of the colony population would occur every 2 years. Colonist groups of up to 22 persons would travel in each habitat vehicle that traveled back and forth between Earth and Mars.

References:

1. Keiffer, H.H. and Zent, A.P., “Quasi-Periodic Climate Change on Mars,” p. 1180-1233 in Mars, Kieffer, H.H. ed., University of Arizona Press, Tuscon (1992).
2. Carr, M-H., Water on Mars, Oxford University Press (1996).
3. Koenig, D.R., “Experience Gained from the Space Nuclear Rocket Program,” Los Alamos National Laboratory, LA, 10062-H (May 1986).
4. Ludewig, H., et al., “Design of Particle Bed Reactors for the Space Nuclear Thermal Propulsion Program,” Prog. In Nuclear Eng., 30, No. 1, p. 1-65 (1996).

3 SELECTION OF A NORTH POLAR COLONY SITE

3.1 Site Selection Issues

Selection of a favorable landing site for the Mars Colony is important. Figure 3.1.1 outlines the important criteria that will affect the choice of a colony site.

First, and very important, is that there be minimum landing problems at the site. The surface should be broad, smooth, and flat with no wind eroded gullies or layered strata that could interfere with the landing process. The margin for landing errors should be wide, to ensure that the vehicles cannot encounter a dangerous gully or other surface features. From orbital photos, there appear to be many potentially good landing sites on the polar cap.

Second, the sub-surface ice structure should be sound, with no discontinuities or major dust strata, for at least ~50 to 100 meters depth. A small amount of dust content can be handled, as noted earlier, but it should be minimized as much as possible, because it makes the deployment and operation of ALPH easier. Similarly, the CO_2 content in the ice should be minimized as much as possible, so that the volume of CO_2 gas released during the sub-surface melt process does not interfere with deployment or the creation of sub-surface cavities for habitats and materials storage.

Finally, the site should maximize, as much as possible, exploration opportunities. Nothing is known about the ice-cap sub-surface structure, geology, composition, etc. Some preliminary information will be obtained from the MICE probes, but much more detailed data can be obtained by exploration from the colony site. This data will provide unique and very important information on the ancient history of Mars, including the possibility of indigenous life forms.

Other factors relating to exploration are the frequency of dust storms that could affect the ability of land rovers or flyers to operate away from the colony site. Other things being constant, a colony site with fewer dust storms would be favored. Finally, a site with easier access to scientifically interesting non-polar regions would tend to be favored.

Data on local ice cap surface and weather condition (i.e., dust storms) relevant to the selection of the colony site would come from orbiter surveys, while data on sub-surface properties would come from MICE probes dropped at candidate locations.

3.2 Exploration of the North Polar Cap by MICE

Obtaining data on the internal structure of the ice cap, in particular, the amount, properties, and spatial distribution of its dust content, is important in the selection of a site for the Mars colony. This data would be obtained from small robotic probes, termed MICE (Mars Ice

Cap Explorer) that would land on the surface of the ice cap. Using a compact, ultra lightweight nuclear reactor as a source of heat and electric power, the probe would melt its way down through the ice, collecting data on the dust content and its properties, as well as a wide range of scientific information about the composition of the ancient Martian atmosphere, solar and cosmic ray activity, and possible evidence of Martian life forms, including wind borne microfossils and DNA traces.

Figure 3.2.1 illustrates the basic MICE concept. The MICE unit melts the surrounding ice using an array of warm water (T ~ 50/ C) jets, carving away the solid ice to form a channel approximately 1 meter in diameter. A portion of the melt water that fills the channel is circulated through the secondary side of a compact heat exchanger attached to the MICE unit, where it is reheated. The warm melt water then flows to the warm water jets. Hot water coolant from the MICE reactor circulates through the primary side of the heat exchanger, providing the thermal power required to heat the warm water jets. The flow rate through the warm water jets is controllable, both azimuthally around the unit and longitudinally along it, so that the shape, size, and angle of the resultant melt channel can be varied as desired. The ability to control the warm water flow pattern, plus the ability to control the thermal output of the MICE reactor, allow MICE to control the diameter of the melt channel, the rate it advances through the ice sheet, and the angle of ascent or descent through the ice.

MICE, for example, can move vertically downwards (mode 1 in Figure 3.2.2), changing its angle of descent both in terms of the angle relative to the vertical, and also its azimuthal angle. MICE can also move upwards and downwards in a series of ascending and descending traverses (mode 2 in Figure 3.2.2) at a controllable vertical and azimuthal angle.

Changing the direction of movement is readily accomplished by locally changing the flow rate of warm water through the jet nozzles. Increased flow on one side of the unit relative to the other side, for example, will cause ice to be preferentially carved away on the side with the greatest flow rate, with the result that the unit will shift in that direction. The shift can be azimuthal or vertical, depending on flow pattern.

The MICE unit has a trailing instrument package, located at a distance of approximately 2 meters from the nuclear reactor. The intervening melt water provides shielding against neutron and gamma radiation, reducing the dose to the instrument package to negligible levels.

In turn, the instrument package trails a thin optical fiber in which data is optically transmitted from the MICE unit back to the lander/transmitter on the surface of the ice sheet.

The melt channel behind the moving MICE unit will refreeze as the thermal energy in the melt water is transferred into the surrounding low temperature (-100/ C) ice sheet. The time to refreeze the melt channel will depend on the channel diameter. The distance of the refreeze point behind the MICE unit will depend both on the channel diameter and the rate at which MICE advances. Typically, the refreeze time (for complete refreezing) will be a few days, and the corresponding distance behind the MICE unit will be on the order of 100 to 200 meters.

The trailing optical fiber will refreeze in place in the frozen melt channel, and continue to transmit data during the full period of the MICE mission.

Figure 3.2.3 shows a simplified view of the MICE reactor. The reactor core is formed as a homogeneous mixture of lithium-7 hydride, which is the moderator, and uranium-235 hydride, which is the nuclear fuel. (The uranium hydride fuel is actually 93.5% U-235 and 6.5% U-238, the standard enrichment product.)

In principle, ordinary water could be used as the moderator instead of lithium-7 hydride. By obtaining the water from melt on surface ice, using an auxiliary heat source on the lander, the weight of the lithium-7 moderator could then be eliminated from the payload. However, although water is widely used and very successful in Earth based reactors, it appears more desirable to use solid lithium-7 hydride for MICE, because it

1. Eliminates the need for a recombiner to reform the H_2 and O_2 from radiolytically decomposed water moderator
2. Enables the use of a smaller, lighter homogeneous reactor rather than a heterogeneous (i.e., fuel rods in water) reactor
3. Reduces the weight of the reactor pressure vessel, due to lower operating pressure
4. Increases the reactor temperature margin compared to that of water,
5. Simplifies the reactor control system

Lithium-7 hydride can operate to temperatures up to its melting point (950 K) without decomposing. Lithium-7 hydride, which has a hydrogen atom density and macroscopic absorption cross section comparable to that of water, is obtained as a by-product from the isotopic separation of lithium-6 from natural lithium. There is a very large supply of lithium-7 (many hundreds of kilograms) in the U.S. stockpile.

The $^7LiH/UH_3$ reactor core is cooled by an array of 84 U-shaped stainless steel/H_2O coolant tubes arranged in a hexagonal lattice (Figure 3.2.3). H_2O coolant flows into the inlet end of the U-tube at the rear end of the core. It then flows through the tube to the front end of the core and returns to the outlet of the tube at the rear end, where it flows into the heat exchanger that heats the melt water for the water jet system.

The reactor core is surrounded by a lithium-7 hydride reflector (without uranium hydride nuclear fuel), which is also cooled by stainless steel/H_2O coolant tubes. The reactor core, reflector, and associated auxiliary equipment (i.e., heat exchanger, mini steam turbine and generator, and control rod assembly) are in turn enclosed by a beryllium pressure vessel.

Detailed 3D Monte Carlo neutronic analyses of the MICE reactor have been carried out using the MCNP computer code (1) and explicit representation of the reactor geometry, examining the effect of various design parameters on reactor size and weight. The results from such MCNP analyses are generally very accurate. In the DOD/SNTP nuclear rocket program (2), for example, MCNP analyses predicted the actual multiplication factors (k_{eff}) for critical PBR (Particle Bed Reactor) reactors to an accuracy of $\pm$ ½%. Power distributions, temperature coefficients, control and worth, coolant worths, etc., predictions, also agreed closely with the experimental values for actual critical reactors.

In the MICE analyses, the effects of coolant tube pitch/diameter ratio, reactor core diameter, reflector ratio, reactor core diameter, reflector thickness, U-235 loading, presence/absence of coolant water, and presence/absence of inserted control rods on the reactor multiplication factor (k_{eff}) were analyzed.

Figure 3.2.4 shows how k_{eff} varies with some of the above parameters. K_{eff} increases with coolant tube pitch/diameter ratio (P/D) because the core is increasing in size (in all cases, it was assumed that the length/diameter ratio [L/D] of the core was constant at a value of L/D = 1), and because the H/U-235 atom density ratio is also increasing. Above a certain P/D value, however, k_{eff} begins to decrease, because the core becomes over-moderated, with excessive neutron absorption in hydrogen. From the standpoint of reactor size and weight, a pitch to diameter ratio of 3/1 appears optimum, as it results in the lowest weight and smallest reactor, the reactor U-235 loading is only 2.18 kg, H_2O coolant worth is reasonably small, and control rod worth relatively high.

Parameters for the baseline MICE reactor design are summarized in Table 3.2.1. Total reactor mass is only 48 kilograms. Based on experimental data for small critical reactors, it appears likely that the above value for total mass can be further reduced by a substantial amount by additional detailed optimization analysis.

A second key aspect of the nuclear design, in addition to minimizing reactor size and weight, is the shielding of MICE's instrument and control package from the neutron and gamma radiation emitted by the reactor. Incorporating shielding as part of the MICE launch package would greatly increase payload weight, increasing the size and cost of the launch vehicle, and make the mission more expensive. However, it appears very practical to use the water in the melt channel as the shielding, as is done in all conventional pool type research reactors.

The instrumentation and control package (I/CP) would trail behind the MICE reactor pressure vessel, attached to it by a short umbilical line (Figure 3.2.5) that would transmit electrical power from the MICE power generation unit to the I/CP and appropriate control signals back to the reactor control rod assemblies, the water jet flow control values, and the coolant pump and power generation systems.

A series of MCNP analyses was carried out to determine how rapidly radiation dose rate decreased with increasing thickness of the water shield between the MICE reactor and the

I/C package. As shown in Figure 3.2.6, the radiation dose rate drops rapidly with water layer thickness, e.g., a 2 meter layer decreases radiation dose by a factor of $\sim 10^7$. In fact, at a distance of 2 meters radiation dose is $\sim 3x10^{-4}$ Rads per second or only about 750 Rads per month of operation at 100 kilowatts (th).

This dose rate appears low enough that the instrument/control package should experience no problems; if it is still too high for certain experiments, however, it could be reduced by a further three to four orders of magnitude by increasing the shielding distance to 3 meters.

Figure 3.2.7 shows the flowsheet for the MICE thermal and electric power system. The MICE core has 2 sets of coolant tubes, comprising a total of 84 u-shaped tubes. Most (~ 90%) of the tubes operate at relatively low outlet water temperature (T_{out} ~50/ C), transferring the output thermal energy through the heat exchanger at the rear end of the reactor to the warm water jet system. The remaining tubes operate at a higher temperature, generating a 2 phase mixture of 250/ C steam and water (~ 30% weight fraction) at their outlets.

The 2 phase outlet mixture flows into a steam-water separator, where the steam and water flows are separated. The separated steam then flows to the inlet (40 atm) of a small steam turbine, while the separated hot water is pumped back to the inlet of the high temperature tubes through the reactor core. The steam-hot water exhaust (1 atm exhaust pressure) from the turbine is condensed in a section of the intermediate heat exchanger, with the thermal energy of condensation transferred to the melt water system to continue the channel melt process.

Table 3.2.2 summarizes nominal design parameters of the MICE thermal and electric power system. These parameters are not optimized, but are reasonably representative values. Film)T's are estimated based on the Seider-Tate equation for turbulent flow inside tubes (3). The Reynolds numbers for the coolant flow are on the order of 10,000. In general, the film)T's, flow velocities, heat fluxes, and internal temperatures in the MICE reactor are far below limiting values. The present MICE design could operate at much higher power levels, a few megawatt (th) without any problems.

The electrical power input of 3 KW(e) would also be greatly increased if desired, by at least an order of magnitude to 30 KW(e). The value indicated here, i.e., 3 KW(e), appears ample to operate the MICE instruments and controls, and to transmit data back along the optical fiber link.

Figure 3.2.8 shows the MICE reactor, together with the heat exchanger and steam turbine-generator, inside its beryllium pressure vessel. Cool melt water flows into the heat exchanger through an intake pipe attached the umbilical line (not shown). After being heated in the exchanger by the circulating reactor coolant water, the warm melt water then flows out of the pressure vessel through an outlet pipe (not shown) to a network of warm water jets arranged around the front end of the pressure vessel.

The flow rate through the various jets is controlled by small individual valves, enabling the local melt rate in the channel to be varied so that the channel direction can be changed if desired. The front end of the pressure has a set of beryllium stand-off tubes, to ensure that the warm water flow from the front of the MICE unit is not obstructed by the pressure vessel pressing up against the solid ice surface.

Figure 3.2.9 shows the length of melt channel produced per day by the MICE unit as a function of reactor thermal power and channel diameter. At 200 KW(th), the MICE channel would advance almost 50 meters per day at a diameter of 1 meter and almost 200 meters per day at a diameter of 50 centimeters. The optimum channel diameter will probably be in the range of 50 to 100 centimeters. Its actual value will depend on the rate data can be acquired and interpreted (too fast a rate of acquisition could overwhelm the capability to gather meaningful data), as well as the efficiency of the warm water jets and the clearance desired between the beryllium pressure vessel and the ice surface.

The MICE vessel has front and rear buoyancy chambers. When both chambers are empty, the unit is designed to be positively buoyant, with its center of gravity at the swivel joint. In the descending mode (Figure 3.2.10) melt water is admitted to the front buoyancy chamber resulting in a overall negatively buoyant condition, with the center of gravity below the swivel joint. The degree of negative buoyancy will be controlled by the amount of melt water in the front buoyancy chamber. In the ascending mode (Figure 3.2.11), the front buoyancy chamber is empty, with melt water admitted to the rear buoyancy chamber, with an overall positive buoyancy for the unit. As in the descending mode, the amount of net buoyancy (negative for descent, positive for ascent) is controllable, by adjusting the amount of melt water admitted into the buoyancy chambers. The swivel joint at the midpoint of the unit enables the umbilical line and the instrument/control package to always trail behind the MICE unit, regardless of whether it is in the descent or ascent mode.

During normal ascent or descent, the diameter of the melt channel will typically be relatively small, probably a meter at most. However, during the transition between modes, i.e., from descent to ascent or vice-versa, a larger diameter melt pool appears necessary, so that the instrument/control (I/C) package can swivel 180/ to maintain its trailing position relative to the MICE unit. (The I/C package will also require buoyancy adjustment when it transitions from the descent mode to an ascent one. This can also be done with buoyancy chambers.)

A melt pool of approximately 3 meters in diameter appears necessary for the transition. Formation of a melt pool of this size will require about ½ day of operation at 200 KW(th). The transition time could be shortened to ~2 hours if the MICE unit operated at higher thermal power, e.g., 1 MW(th). Determining whether having a shorter transition time warrants designing for higher power capability requires further study.

In addition to obtaining data on the local properties (e.g., dust and CO_2 content) and internal structure (e.g., layered or uniform) as an aid in selecting the site for a Mars colony, MICE will also gather data on the geology history of Mars. Figure 3.2.12 illustrates the types of data MICE could acquire about the history of the ancient atmosphere of Mars, its ice cap, and its geology, while Figure 3.2.13 gives examples of the instruments and techniques that could be used to gather the desired data.

The ability to date the age of ice deposits as a function of their depth and latitude/longitudinal position is highly desirable. ^{14}C dating of trapped Martian atmosphere in the ice appears to be a promising approach, but would only provide information up to an age of about 50,000 years. Since the areal mass density of the Martian atmosphere is only about 1% that of Earth, its shielding capability against cosmic rays will be minimal. The residual activity of cosmic ray induced radioactive spallation products in dust grains trapped in the ice should yield information on the much older deposits presumably located deep inside the ice cap. ^{26}Al, for example, has a half life of 730,000 years, with a high energy (1.8 MeV) gamma emission. A wide range of spallation products should be available for dating.

The amounts of ^{4}He and ^{3}He trapped in the ice sheet should provide data on the time history of solar wind activity. The low areal density of the Martian atmosphere also helps in this regard. Extracted gas samples could be cooled to cryogenic temperatures to condense out background gas, and then analyzed by mass spectroscopy to measure the ^{4}He and ^{3}He content.

Of particular interest and importance would be the detection of primitive Martian life forms, either as microfossils, actual frozen bacteria, or spores, or biochemical residues (DNA, etc.). Microscopic examination, PCR techniques, chromatography, etc. could all be used to detect evidence of ancient or existing life. In this connection, it appears likely that over the ~4 billion year period that life has existed on Earth, a substantial amount of Earth material, many millions of tons, has been transported to Mars as a consequence of asteroid impacts (4). It would be extremely interesting if MICE were able to detect evidence of such transport, and in particular, the transport of life related material.

Initial MICE missions would probably operate only in a data acquisition mode. However, as discussed later, it appears practical to transport large amounts, e.g., hundreds of kilograms, of material from the ice cap back to Earth, using H_2/O_2 propellant derived from the ice sheet. The material returned would include samples of the ancient atmosphere and wind carried dust grains, together with material that might be evidence of the presence of ancient or existing life.

Figure 3.2.14 outlines the two types of MICE missions considered: a data only mission (Mission 1), and a data and sample return mission (Mission 2) in which samples from the ice cap are returned to Earth.

The MICE units are basically the same in both missions, except for the following differences:

1. In Mission 1, the MICE unit does not have to return to the lander. In Mission 2, the unit must return to the lander and transfer the collected specimens.
2. In Mission 2, before it starts into the ice cap, the MICE unit provides electrical/liquefier unit on the lander, generating H_2/O_2 propellant for the return trip.

The electrical power for this operation will have to be substantially greater than the 3 KW(e) assumed for Mission 1. At 20 KW(e), it would take approximately 5 weeks to produce the H_2/O_2 propellant for the return trip. The higher power turbine/generator could be incorporated into the MICE unit, or remain in place on the lander. The H_2 and O_2 on the lander would be kept cold during MICE's travel through the ice cap by a small cryo-cooler powered by a H_2/O_2 fuel cell. The amount of extra H_2/O_2 used would be small compared to that produced for propellant.

Table 3.2.3 shows a mass budget for the MICE unit including all of the necessary hardware. The total is ~200 kg, including a 50 kilogram contingency. The reactor weight can probably be reduced by ~10 kg with a more optimized design. However, the instrument control package will probably grow in weight, using up some of the contingency. Adding in the weight of the lander, transmitter, and aeroshell brings the total weight of the MICE payload to ~400 kilograms.

Overall parameters for the 2 MICE missions are summarized in Table 3.2.4. The nominal departure date is for illustrative purposes only. In practice, MICE probably could be ready by 2006 or 2007. Both missions would be carried out using a relatively low cost Delta II launch vehicle. The MICE outward bound payload is taken as 600 kg for Mission 2, reflecting the greater weight associated with the sample return mission. A 200 kg sample return payload is assumed, which sizes the return lander and the amount of H_2/O_2 propellant required for production on Mars.

A detailed description of the ALPH concept is later. The ALPH concept, which uses a small robotic nuclear reactor powered unit landed on the North Polar Cap would produce many tons of liquid H_2, liquid O_2, liquid methane, methanol, and plastic construction materials, together with tons of food, using only ice and the Martian atmosphere in advance of the arrival of astronauts at the base. Virtually all of the supplies required for the base would be in place when the astronauts arrived, stored in sub-surface chambers melted from the ice sheet by the ALPH unit. The ALPH unit would also create sub-surface habitat chambers for human occupancy, which would be pressurized and shielded from cosmic rays.

MICE is an important precursor to the ALPH manned base approach, as outlined in Figure 3.2.15. It would provide data on the ice cap structure and the melt channel formation process, as well as demonstrate the in-situ production of H_2 and O_2 from Mars ice. A high power version of the MICE reactor could be used for ALPH.

Development of the MICE system appears as primarily an engineering systems development program rather than one that has to develop new types of materials or micro-miniaturize existing technologies. The MICE reactor and power system uses well established existing materials, and the operating temperatures and power densities are very conservative. The thermal hydraulics of the melt channel process appears straight forward and the required technology sample. The process can be readily tested in existing ice sheets on Earth, using electrically heated units.

Phase 1 (Figure 3.2.16) involves 3 main tasks: 1) testing electrically heated MICE units in Earth ice sheets, 2) building and testing the MICE reactor and power system, and 3) developing and testing the MICE instrument package. This latter task probably involves the most effort in Phase 1, since it is desirable to maximize the amount and quality of data obtained by a MICE mission. In Phase 2, all of the MICE system components would be integrated into a single unit, which would be tested in an Earth ice sheet. After validation, the final MICE payload would be ready for launch.

The total development time until launch for the program is estimated at about 7 years. This could probably be reduced to approximately 5 years, depending on the sophistication of the instrumentation that mission planners would require. The amount and degree of instrument development, together with functioning level, probably would be the primary factors determining the length of the development program.

References:

1. Breismeister, ed., "MCNP, A General Monte Carlo Code for Neutron and Photon Transport, Version 3A," LANL, LA 7396-MS, Rev. 2 (1986).
2. Ludewig, H., et al., "Design of Particle Bed Reactor for the Space Nuclear Propulsion Program," Programs in Nuclear Energy, 30, No. 1 (1996).
3. Knudsen, J.G., "Heat Transmission," Section 10 in Perry's Chemical Engineer's Handbook, 5th ed., McGraw Hill (1973).
4. Nealson, K., AUI Distinguished Lecture, Brookhaven National Laboratory (June 23, 1999).

4 DESCRIPTION AND PERFORMANCE OF THE ALPH ROBOTIC FACTORY

4.1 Features of ALPH

In the ALPH (Atomic Liberation of Propellant and Habitat) concept, autonomous, lightweight robotic landers generate electric power, create habitats, and process indigenous resources to manufacture and stockpile propellants, fuel, construction materials, breathable atmosphere, and food. The ALPH approach enables manned missions from Earth with minimum launch requirements and costs, since crews need not carry large amounts of return propellants, supplies, and equipment with them. Virtually all of the materials needed to perform their mission and return safely to Earth will be already waiting when they land at the outpost. Figure 4.1.1 summarizes the principal features of the ALPH system.

The ALPH outposts would be located on the Martian Polar Caps, and in particular on the North Polar Cap. After touchdown on the surface of the ice sheet, the ALPH lander deploys its energy source, a compact, lightweight nuclear reactor, to melt channels down into the ice sheet and generate electric power. The ALPH reactor and power generation systems employ very conservative, very well developed technology that has been used for over 30 years. The outlet temperature (~250/ C) of the water coolant is lower than the ~ 300/ C used in commercial LWR power reactors. Power is generated by a conventional steam turbine coupled to a conventional 400 Hz electric generator. Overall power cycle efficiency is a conservative 20%, less than the 32% efficiency for LWR power reactors. Waste heat is either rejected to the surrounding ice sheet, or radiated from a surface cooling pond.

Waste heat from the ALPH reactor creates large cavities inside the ice sheet for habitats and storage of the manufactured propellants, fuel, and breathable atmosphere. The various process units remain with the lander package on the surface of the ice sheet while the ALPH reactor and its integral power generation system melts its way down to a position well below (i.e., at least 10 to 20 meters below) the surface. The intervening ice acts as shielding for the human occupants.

The habitat cavities are located well below (i.e., at least 10 meters below) the surface, so as to provide shielding against cosmic rays. Unprotected humans on the Martian surface would experience ~ 50 Rem per year. With 10 meters of ice, the shielding is equivalent to that of Earth's atmosphere. Cavities for propellants, fuels, and oxygen are also located below the surface, and isolated to prevent any problems if leakage were to occur.

A small electrolyzer process unit on the lander package generates hydrogen and oxygen gas from the melt water. The hydrogen and oxygen are in turn liquefied by small, electrically powered refrigerator/liquefiers and stored in sub-surface cavities. Process water and electric power are supplied by small pipes and power cables that connect the lander to the subsurface ALPH/power generator unit. Using the CO_2 atmosphere on Mars, additional small process units (Figure 4.1.2) on the lander produce other fuels (i.e., methanol and liquid methane) using some of the generated hydrogen. Plastic construction materials and insulation (e.g., polyethylene, polystyrene, etc.) are also be produced. Food is produced and stored (i.e., algae and yeast) together with a breathable air supply.

Nominal parameters for an ALPH lander are: 2.7 MW reactor thermal power, 535 KW(e) electrical power, with the capability to generate each month of operation over 10,000 cubic meters of cavity volume, 40 metric tons of liquid oxygen, 4 tons of liquid hydrogen, 3 tons of liquid methane and methanol, a ton of plastic construction material, and hundreds of kilograms of food. The ALPH outpost could support many persons, with fuel and oxygen for long distance exploration using land rovers, atmospheric flyers, and ballistic hoppers. The weight of the ALPH lander is estimated to be ~5 metric tons. Each outpost would probably have two independent ALPH landers for redundancy and reliability. The landers would touch down approximately two years before humans left Earth, allowing a very large inventory (i.e., many tons) of stockpiled supplies and materials to accumulate in advance of the manned mission.

The concept of using indigenous resources for manufacturing materials for Martian manned missions is not new. Zubrin (1), for example, proposed making CH_4 propellant on Mars to reduce IMLEO requirements. Subsequent discussions with the NASA Johnson Space Center Explorations Office produced a modified MARS Semi-Direct Architecture (2) which eliminated some problems in the original MARS Direct Plan.

However, the earlier concepts for using indigenous Martian resources suffer from two major drawbacks. First, because the landing sites are typically located on a dry plain with no available H_2O (the presence of sub-surface H_2O is uncertain), the amount of material that can be produced is very limited. Second, the lack of a large, low temperature heat sink severely limits the amount of electric power that can be generated and necessitates the development of a new high temperature nuclear power source.

As a result, mission capabilities tend to be strongly constrained, with very limited ability to carry out long range exploration, and little margin for unexpected crises. In contrast, with the ALPH approach, because of the unlimited, simple low temperature heat sink, extremely large amounts of material can be produced enabling a very robust long range exploration program. The apparent disadvantage of being located on the North Polar Cap is not really a drawback. In fact, the Polar Cap can serve as a smooth, readily traversable roadway for rovers to reach a very large area of the Mars surface (minimum Polar Cap diameter is 1000 kilometers). Also, the large amounts of liquid fuel and propellants produced by ALPH make practical numerous trips by long range flyers and ballistic hoppers. Moreover, the sub-surface cores of the North Polar Cap can provide a very valuable record of the Martian climate for many millions of years in the past.

4.2 Landing and Deployment of ALPH Prior to Arrival of Colonists

Figure 4.2.1 illustrates the operational steps involved in establishing the colony. The first step is the launching of ALPH from Earth to Mars. The only requirement for the ALPH landing site is that it be on an ice sheet that has a minimum thickness of several tens of meters, with a sufficiently broad extent to ensure that the lander has a high probability of landing on a flat, relatively smooth surface. Previous exploration of the North Polar Cap by MICE robots will have determined a suitable site for the ALPH landing.

Once landed, the ALPH package would deploy and begin operation. The reactor would thermally melt its way downwards through the ice, creating sub-surface cavities where appropriate. Secondary thermal melt lines would also be deployed from the lander package. These lines, which are connected to the reactor thermal circuit, would in turn melt their own way through the ice, creating additional cavities (where desired) that were isolated and at some distance from those created by the descending reactor. The reactor would be integrated with a small lightweight steam turbine for electric generation into a compact unit (~ 1 meter in diameter) that melted a channel down through the ice. The generated electric power and hot water from the reactor/generator unit would travel upwards through cables and pipes to the surface lander package and the secondary thermal melt lines.

Process units on the lander package would produce various products for the outpost. These products (e.g., liquid hydrogen propellant, liquid oxygen, liquid methane, gaseous oxygen, plastics, etc.) would be transported by pipes attached to the secondary melt lines to the various sub-surface habitat and storage cavities created by ALPH. For example, liquid H_2 would be transported by a small diameter flexible cryogenic transfer line to a sub-surface, thermally insulated, cavity for storage.

Three types of deployment configurations appear possible with ALPH. In the linear vertical configuration, the ALPH reactor vertically descends in a melt channel that is approximately one meter in diameter. Habitat and storage cavities are created along the line of descent. The cavities can either be formed behind the descending ALPH reactor as it moves downwards or the ALPH reactor can descend to its final position beneath the ice sheet, and the cavities then created at appropriate points along the pipe/cable bundle. The latter method is probably preferable since it involves a simpler and easier uncoiling of the pipe/cable bundle. Only a single large coil is required on the lander package. As the ALPH reactor descends, the coil would pay out the required length of pipe/cable bundle to enable it keep moving downwards. The principal issue for the linear vertical configuration is that a depth of at least 50 meters is needed to accommodate the habitat and storage volumes. Even in reduced gravity, the resultant pressures and stresses in the walls of the deeper cavities could be excessive. For a Mars, for example, with a g of 3.8 $msec^{-2}$, cavity walls at 100 meters depth would experience a pressure of 3.8×10^5 N/m^2 (~ 60 psi) which might cause ice flow or cracking.

The second option is the branched horizontal configuration. Secondary warm water pipe bundles are first deployed horizontally outwards from the lander package. Each secondary pipe bundle is heated by warm water so that it moves downwards through the ice sheet, creating a melt channel until the desired depth is reached. The warm water lines would then melt cavities around the pipe bundle. The horizontal branched configuration allows multiple cavities to be created at modest depths azimuthally spaced around the lander package. The principal issue for the horizontal branched configuration is the horizontal deployment of the warm water pipe bundles, probably by small, lightweight wheeled vehicles. Although this appears practical, it increases lander weight and complexity.

The third and preferred, option is the angled branched configuration shown in Figure 4.2.2. Unlike the horizontal branched configuration, deployment of the warm water lines proceeds directly from the lander package. In the linear vertical configuration, multiple cavities can be created at modest depths, without having to descend to 50 meters or more. The optimum angle of deployment will probably be on the order of 45 degrees. Figure 4.2.3 shows a top view of the angled branched configuration, with the cavities azimuthally spaced around the lander.

The ALPH payload consists of the ALPH reactor/power system unit, the coiled flexible pipes (warm water and process fluids), electric cables and various process units. After touchdown, the lander pads would be thermally heated so that they would sink into the ice sheet for ~20 to 30 centimeters. The heating then ceases, allowing the pads to freeze into the ice sheet, preventing tipping or movement of the lander package. The ALPH reactor then is lowered to the surface of the ice sheet, where it would startup and proceed to carve a melt channel downwards. The water inventory for ALPH would probably not be carried in the lander package, but would be obtained from melting of the ice by a small auxiliary chemical based heat source (1 kg of chemical fuel would melt approximately 30 kg of ice) or a small auxiliary solar electric power source (1 kW thermal of incident solar radiation converted at 10% efficiency would melt 20 kg/day of ice). Using the chemical option, water for the ALPH reactor and coolant circuit would be available in a few hours; using the solar cell option, it would take a few days. The principal parameter for the ALPH reactor and thermal power system are given in Table 4.2.1.

Figure 4.2.4 illustrates the geometry of the unit that melts the channel downwards through the ice sheet (operational phase #2). The leading section of the unit is a warm water heated metal shell, made of aluminum or beryllium, that directly contacts the ice, melting the ice beneath. Figure 4.2.4 shows the construction of the melting unit attached to a secondary warm water line. Warm water from the lander package flows down through one of the small diameter pipes in the pipe bundle, through passages in the metal shell, and returns through another small pipe in the bundle. The melt water generated by the heated shell trickles through small holes in the shell, accumulating behind it, where it would be sucked away by a third small tube in the bundle. (If a melt channel is not pressurized, a small pump provides the head needed to lift the melt water to the surface of the ice sheet.) Figure 4.2.4 also shows the collapsed melting balloon around the pipe bundle, which would be inflated in operational phase #3. The melt channels for the secondary warm water lines are approximately 0.6 meters in diameter. The melt channel for the ALPH reactor unit is not shown, but would be somewhat larger, about 1.0 meter. The reactor, steam turbine, heat exchangers and melt shell form an integral unit that descends through the ice sheet.

The melt channel can be vertical or angled, as indicated in Figure 4.2.4. The descent rate, i.e., the rate at which the unit moves through the ice sheet, is controlled by the amount of thermal power fed to the melt shell. Figure 4.2.5 shows the melt rate as a function of the heat flux into the ice from the melt shell. At a heat flux of 1 watt per cm^2, which can be readily supplied, the melt shell would move through the ice at ~2 meters per day. Doubling the heat flux increases the rate of advance to almost 4 meters per day. Such rates would allow ALPH to deploy in a few weeks at most, even for the linear vertical configuration. The thermal power depends on the heat flux and the diameter of the melt shell. Even at the higher heat flux of 2 watts per cm^2 and the larger diameter shell, i.e., 1 meter, the required power is small - only about 15 kilowatts, or about 2% of total reactor power.

Figure 4.2.4 shows that the melt shell can move vertically downwards or at some desired constant angle with respect to vertical. For the condition, the heat flux per unit <u>projected</u> area ahead of the shell must be constant, since the <u>volume</u> melted away per unit time is constant over the same projected area. If it is desired to <u>alter</u> the angle of descent, the heat flux per unit projected area can be made larger at one side of the melt shell than at the other side. The melt shell will then move toward the side of the channel where the heat flux is greater. The magnitude of the heat flux gradient between the sides of the melt shell will control the rate at which the angle of the melt channel changes. The angle of the melt channel relative to vertical can be measured by a simple pendulum. Measurement of the azimuthal angle can be done with small solid state accelerometers or gyroscopes.

After deployment of the reactor and secondary warm water lines has been completed, <u>operational phase #3</u>, the creation of the sub-surface cavities, would begin. Figure 4.2.6 shows the diameter of the cavity as a function of time after the melt balloon begins to operate, for heat fluxes of 0.05 and 0.10 watts per cm^2 at the surface of the balloon. To create a 10 meter diameter cavity at 0.1 watts per cm^2 would take approximately 27 days; at 0.05 watts per cm^2, it would take twice as long, or about 54 days. The corresponding maximum thermal power (i.e., the thermal power required at the end of the cavity forming process) is ~500 kilowatts for 0.1 watts per cm^2 heat flux, and ~250 kilowatts at 0.05 watts per cm^2, based on a final cavity diameter of 10 meters and a length of 15 meters. These thermal powers are very reasonable and represent the maximum power required. The average thermal power is only ½ of the maximum value. Accordingly, a 2.7 MW(th) ALPH reactor with a thermal waste heat output of 2.1 MW could form 8 such cavities (i.e., 10 meters in diameter and 15 meters long, in about a month.

Figure 4.2.7 shows the construction of the melt/thermal insulation balloon. The final shape and size are determined by the dimensions of the fine mesh net bag that encloses the actual balloon. The strands of the net bag are assumed to be made of Spectra, a high strength drawn polyethylene fiber, with a tensile strength of ~3 Gpa (~450 ksi) and a density of 0.9 $g/cm^{2.}$.

The hole size of the mesh bag is a few millimeters - small enough to support the skin of the bag, but large enough to easily fabricate. Its construction is analogous to the netting used on atmospheric balloons. The mass of the mesh net bag is small. For example, assuming a nominal diameter of the balloon of 10 meters and an internal pressure of 50 kPa (7.5 psi), the mesh bag has a mass of only 150 kg for a 10 meter length, based on a conservative tensile stress of 0.5 gPa (75 ksi) in the Spectra strands. With more detailed design, the internal pressure in the balloon could be lower and the operating stress in the Spectra strands higher. For example, decreasing the internal pressure to 25 Kpa (~4 psi) and increasing the tensile stress to 25% (0.75 Gpa) of ultimate stress, would reduce the mass of the net bag to only 50 kg for a 10 meter length.

The continuous plastic film skin of the balloon inside the net bag has internal passages carrying the warm water that melts the ice cavity. Based on an average heat flux of 0.1 $watt/cm^2$ and a 10 meter long balloon, 100 watts of thermal power is required per centimeter of distance around the azimuthal perimeter of the balloon. This low thermal load can be easily handled by water flowing through the balloon skin. If the temperature drop of the water flowing from the inlet of the balloon skin to its outlet is taken as 5/ C, the corresponding volumetric water flow rate would be 25 cm^3 per sec, per centimeters, the flow velocity is then only 25 centimeters per second. The total pressure drop along the 10 meter flow path is then only ~10^4 Pa (~1 psi).

After the cavity has reached its final dimensions and the balloon is fully inflated, the water inside is expelled by in-flowing gas. The collapsible insulation cell on the inside of the skin is inflated by gas maintained at a slightly greater pressure than the gas inside the main body of the balloon. When inflated, the gas insulation cells are on the order of 1 centimeter in diameter. This is small enough that natural convection inside the cells does not occur. The heat flux through the gas insulation layer is then determined by the thickness of the layer and the thermal conductivity of the gas.

Figure 4.2.8 shows the heat fluxes through the insulation layer for 4 cases: 1) liquid H_2 propellant cavity ($T_{interior}$ = 20 K), 2) liquid O_2 propellant cavity ($T_{interior}$ = 90 K), 3) liquid CH_4 cavity ($T_{interior}$ = 112 K), and 4) habitat cavity ($T_{interior}$ = 300 K).

In the above cases, a constant ice sheet temperature is assumed, with a value of -100/ C (173 K). In the first 3 cases, the gas inside the insulation cells has the same composition as the material inside the storage cavity - i.e., H_2 in case 1, O_2 in case 2, and CH_4 in case 3. In case 4, the habitat cavity and insulation layer both contain air. The cell insulation inner layer immediately adjacent to the stored propellant has a smaller cell size - on the order of 0.1 centimeters - so that cells that contain liquid do not undergo natural convective heat transfer. This inner layer is much thinner (~1 centimeter) than the overall thickness of the insulation layer.

The heat fluxes vary inversely with insulation layer thickness. In cases 2 and 3, with an acceptable heat flux on the order of 10 watts per m^2, this corresponds to a heat flux of 3 KW(th). A representative refrigeration factor for the cryogenic conditions in cases 2 and 3 [thermal input at ~100 K; heat sink at 173 K (ice sheet temperature)] is on the order of 3 watts (e) per watt(th), or about 25% of Carnot efficiency. The corresponding refrigeration input electric power to the refrigerator to maintain the O_2 or CH_4 propellant in the cavity is then ~10 kilowatts.

For case 4, the acceptable heat flux outwards from the habitat cavity is ~20 watts per m^2. No refrigerator is needed, since the heat leakage is absorbed and dissipated in the large volume of the surrounding ice sheet. For cases 2, 3, and 4, an insulation layer thickness of ~15 centimeters is sufficient to keep the internal temperature at the desired value, the minimal effect on power requirements, or thermal dissipation in the ambient ice sheet.

The insulation requirements for the liquid hydrogen cavity (case 1) are more demanding. The insulation barrier is split into 2 regions - an inner region that operates between 20 K and 80 K, and an outer region that operates between 80 K and 173 K. The 80 K boundary is maintained by a separate refrigeration circuit from the one that keeps the liquid hydrogen at 20 K. For a cavity with 300 m^2 surface area, the heat leak into the 20 K region is 1.5 KW(th) at a heat flux of 5 watts per m^2. The refrigeration factor for the inner insulation in case 1 [thermal input at 20 K; heat sink at 173 K; 25% of Carnot] is 30 watts(e) of electric input power per watt(th) of thermal input to the 20 K region. The corresponding refrigeration input electric power for the liquid H_2 is then 30 x 1.5 or 45 KW(e). This is only about 10% of the ALPH output electric power.

A heat leak rate of 5 watts per m^2 corresponds to a insulation thickness of ~60 centimeters. An additional thickness of ~15 cm is required between the 173 K ice boundary and the intermediate 80 K heat sink, making the total insulation thickness equal to 0.75 meters, as compared to the cavity diameter of ~10 meters. The balloon skin can also be reinforced by incorporating high strength plastic fibers in the plastic matrix of the skin, instead of having an external fine mesh net bag. Such a construction would make it easier to collapse and pack the balloon around the pipe bundle. Experiments and tests of different balloon construction methods should be carried out before making a definitive choice of the method for the Xanadu outpost.

The method for sealing the cavity, <u>operational phase #5</u>, is illustrated in Figure 4.2.9. The seal-off region is several meters in length. Water is pumped into the previously formed melt channel and then freezes as it is cooled by the surrounding low temperature (e.g.,

~100/ C) ice sheet. The sealing region is first isolated from the other sections of the melt channel by two hydraulically inflated pressurized balloons that press against the surrounding ice (Figure 4.2.9). The sealing region between the two balloons is then filled with melt water which freezes, forming the finished seal. The melt channel diameter for the secondary warm lines is ~0.6 meters, and ~1.0 meter for the ALPH reactor. The refreeze time will be on the order of a few hours for a 0.6 meter diameter channel and approximately a day for the 1.0 meter channel.

4.3 ALPH Reactor and Power System

The ALPH Reactor Power Generation System is based on established and proven technology. A new kind of reactor does not have to be developed, and the power generation system is based on a conventional steam turbine Rankine cycle. The only development required is to design the components using known materials and design codes, and to integrate the components into a launch package that is space qualified and will be suitable for operation on Mars.

Two reactor options have been investigated. Both are based on available components, and operate well within the bounds of known technology. In the first option, the reactor fuel elements are based on the proven Materials Test Reactor (MTR) type element. This type of element has been operational in reactors since the 1950's. They consist of a box shaped element with multiple internal curved plates. The outside dimensions of the elements are typically 7.5 cm x 7.5 cm (3 inch x 3 inch) and have 18 to 20 plates. The length of the fueled section of the element is 24" (60 cm). Cores of various sizes can be built up depending on the fuel type, enrichment, loading, and reflector. All the cores are 60 cm in height. Both light and heavy water have been used to cool MTR type cores. The applications to date have been primarily based on using aluminum as clad and structural material. Typical examples of such reactors are the Bulk Shielding Facility and the Low Intensity Test Reactor both at ORNL, and the Material Test Reactor at INEL. Power levels for these reactors varied from 500 kW to 40 MW.

The ALPH version on the first option is based on the core of the High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL). The HFBR can operate at power levels of 60 MW. Its fuel elements are of the MTR type described above (Figure 4.3.1). It uses fully enriched fuel in the form of U3O8, and aluminum is used as the clad and structural material. The maximum power density in the HFBR is approximately 1.4 MW/L, with a water coolant velocity of approximately 10 m/s. Since, the coolant outlet temperature on the ALPH reactor is greater than 200 C, zircaloy is chosen as the clad and structural material. Zircaloy is commonly used in commercial LWR's, and does not require additional fuel element development work. Light water is used as both coolant and reflector (minimum thickness 15 cm) for the system instead of the heavy water used in the HFBR.

The ALPH with 25 fuel elements (5 x 5 array) and a 15 cm minimum thickness light water reflector has a multiplication factor (ke) of 1.286, assuming an enrichment and uranium loading per element equal to that in the HFBR. This corresponds to a core uranium loading of 9 kg. Since the operating power level for the ALPH reactor is ~2.7 MW(th) it could operate for years before requiring re-fueling. With approximately the same uranium loading the HFBR operates 22 days at much higher power levels before changing a quarter of the fuel elements. The average power density in the ALPH core is a factor of ~30 lower than in the HFBR. The lower power density would allow operating times of several years before the multiplication factor decreased to the point where the reactor was not critical. Longer operating times can be achieved by incorporating a burnable poison and more U^{235} in the fuel elements. The lower power density in the core also allows the coolant flow rate (assuming approximately the same heat transfer area) to be proportionately lower. Thus for the same film drop, the velocity can be as low as 1 m/s. Finally, since zircaloy is used as the clad material a higher film drop is acceptable, further reducing the requirement for high coolant flow velocity.

The core and reflector diameter for the above arrangement is 73 cm. The core is controlled by axial control blades by inserted from the top. The fail safe position of the control blades is inside the core, which is located at the bottom of the pressure vessel. Steam generators for the steam power cycle are placed at the top of the pressure vessel. The control blades are internal to the vessel and actuated by a hydraulic drive system. A schematic of the lower half of the pressure vessel with the ALPH reactor is shown in Figure 4.3.2. The core is shown in the bottom of the vessel, surrounded by the returning coolant from the steam generators, which also acts as the radial and axial reflector. Coolant flows axially up through the core, through the steam generator tubes, and then down past the outside of the reactor core. Circulating units, if required would be located at the outlet of the core in the chimney leading to the steam generators. The circulators would be powered by hydraulic units enclosed in the pressure vessel, minimizing the possibility of seal leaks. The control blades are arranged around the axial up flow chimney.

Steam generated on the shell side of the steam generator is separated in a steam separator similar to those used in commercial BWR’s. The steam separators are located above the steam generators, and feed the steam turbine. The secondary side operates at approximately half the pressure of the primary system, and will have a saturation temperature of 520 K. Feedwater for the steam generators is pumped in by electric powered feed pumps. The primary side is maintained at desired pressure by a pressurizer located above the vessel. The steam generator tubes, pressure vessel, and pressurizer are made of titanium.

The second option for ALPH is to use the MICE reactor, which would be smaller and lighter than the HFBR type reactor. The MICE parameters shown in Tables 3.2.1 and 3.2.2 correspond to a thermal power of 200 KW (th) for the MICE reactor. The ALPH reactor thermal power (2.7 MW(th)) is a factor of 13 greater. The power of the MICE reactor design presented here can be considerably increased by increasing water flow velocity in the coolant tubes; from 1 meter/sec to 5 meters/sec, and the ΔT across the core, from 20° C to 30° C.

With the adjustments, the MICE design could achieve 1.5 MW(th). To reach 2.7 MW(th), the core diameter would be increased somewhat from 29 centimeters to 35 centimeters. The number and diameter of the coolant tubes would be increased.

There are significant advantages to choosing the MICE reactor option for ALPH instead of the plate type reactor. These include:

- Less R&D (one reactor type, not 2)
- Reduced weight
- Simpler design
- Easier long term control with burnable poison

At this point, the MICE option appears preferred for ALPH.

4.4 Fuel/Propellant Production

Figure 4.4.1 shows the overall flowsheet for the production of fuel and propellants. A portion of the H_2 and O_2 produced by the ALPH electrolyzer is first cooled to the temperature of the surrounding ice sheet (-100° C), and then by heat exchange with a closed cycle refrigerator that employs an inverse Brayton cycle with Helium gas working fluid.

The low heat sink temperature (-100° C) available in the surrounding ice sheet greatly reduces the power requirements for cryogenic liquefiers operating on Mars, as compared to operating on Earth. The Carnot coefficient of performance for refrigeration at 80 K, for example, corresponds to only 2 watts(e) input power per watt(th) refrigerated at 80 K. For an actual refrigerator operating at 25% of Carnot efficiency, the actual input power would only be 8 watts(e) per watt(th) of refrigeration.

For methane fuel, H_2 from the electrolyzer would be reacted with atmospheric CO_2 to produce methane using standard conversion technology. A portion of the methane would be further reacted to make methanol fuel, again using standard conversion technology.

4.5 Breathable Air Production

Figure 4.5.1 shows the flowsheet for the production of breathable air. Pure oxygen obtained from the H_2O electrolyzer (there is a substantial surplus of oxygen left over from the H_2 production), would be mixed with nitrogen extracted from the Martian atmosphere. The 79% N_2/ 21% O_2 mixture would then be liquefied and stockpiled in storage cavities inside the ice sheet.

The Martian atmosphere contains 95% CO_2, 2.7% N_2, 1.6% Argon, and various minor constituents. The extraction process shown in Figure 4.5.1 appears to be a simple, low energy requirement separation process. The Mars atmosphere is first compressed and then cooled to the temperature of the surrounding ice sheet, which causes most of its CO_2 to condense and freeze out. The remaining compressed gas is then expanded in a turbine to 1 atmosphere, which drops its temperature to ~100 K. Virtually all of the remaining CO_2 freezes out, leaving a mixture of nitrogen and argon gas. The mixture is then liquefied and cryogenically distilled to reject argon.

As the last step, the remaining purified nitrogen is mixed with oxygen to form a 79% N_2/21% O_2 air, which is then sent to a storage cavity.

4.6 Construction Materials Production

Figure 4.6.1 shows an overall flowsheet for the production of construction materials using ALPH. In order to minimize the complexity and weight of the process unit that produces construction materials during the robotic operational phase of ALPH, only the simple $(CH_2)_n$ polymers, such as polyethylene, polypropylene, etc, would be manufactured.

The properties (tensile strength, etc.) of the above product depend on process conditions - temperature, pressure, catalyst type, etc. - J which can be tailored to give whatever final properties are desired. Determination of the optimum process and process conditions to be used is beyond the scope of this study.

The first step is the preparation of the appropriate synthesis gas, followed by polymerization, and finally by separation and storage of the product polymer.

The first colonists would use the stockpiled polyethylene or polypropylene to manufacture furniture, piping, clothing, space suits, first generation rovers and unmanned flyers, etc., along with additional process units to manufacture more complex products.

The lower half of Figure 4.6.1 shows some of these more complex products. They include a wider range of plastics, such as polyesters and epoxies that can be used to make high strength composites. These composites would utilize high strength plastic fibers such as

Kevlar and Spectra (stretched polyethylene) and graphite fibers, which would be manufactured by decomposition of methane.

Mars dust collected from the ice cap would be processed to manufacture iron based metals from its iron oxide contents, and aluminum and magnesium from its aluminum and magnesium oxides.

A variety of ceramics products would also be manufactured from Mars dust, including glasses, glass fibers for composites, refractory blocks, polymer concrete, etc.

4.7 Food Production

The simplest and most efficient way to robotically produce and stockpile food at the colony site in advance of the first manned landing party is to grow algae and yeast in small bio-reactors. Figure 4.7.1 shows the overall flowsheet for algae and yeast production. Each type of food material would be grown using as inputs an organic substrate, water, light, and appropriate micro-nutrients. Possible substrates include alcohols (e.g., methanol or ethanol), alykatic long chain hydrocarbons, methane, etc. Light would be supplied by Light Emitting Diodes at the optimum wavelength for effuse growth.

The produced algae and yeast would be separated out, frozen, and stored in cavities in the ice sheet to await the astronauts arrival.

Yeast and algae have already been commercially produced in large tonnages and used for nutritional purposes with genetic engineering, it appears likely that their nutritional properties can be further optimized, and growth rates increased. The production rates are already high, and the corresponding bioreactors are small, on the order of 100 liters in volume, which would produce the food for the first landing party.

While nutritionally adequate, a diet consisting solely of algae and yeast would be somewhat boring, even when textured into appealing forms and flavors. After the astronauts arrival, additional types of food could be produced using the algae and yeast as feed for shrimp and fish in water ponds located inside the ice sheet for example, or by hydroponics.

4.7.1 Background

Food production, whether in low earth orbit (LEO) for the International Space Station (ISS), or on Mars for future manned missions, presents many new and unique challenges not addressed by previous manned missions. Whereas life support for previous missions dealt chiefly with oxygen supply, carbon dioxide removal, water recycling, and temperature control, food production involves monitoring and maintaining a complex living system. Due to the necessarily long duration of the proposed manned mission to Mars, the use of shipped and resupplied food as the main source of food for the crew will require very high Initial Mass to Low Earth Orbit (IMLEO). Studies of the cost of resupplied food versus locally produced food concluded that a LEO mission with 50% food closure was less costly than food resupply after only 2 months (MacElroy and Bredt 1984). The costs for resupply to Mars, of course, are very much more expensive even for a mission with 50% food closure and a minimal 95% closure rate would be desirable.

Towards this goal, the NASA program for Controlled Ecological Life Support System (CELSS) was established to research bioregenerative food production. Most studies have focused on the use of higher plants or algae to both produce food and recycle gases and water. Much work was done on improving the productivity of certain high yield crops such as wheat and sweet potatoes, and under controlled conditions yields of 17.7 g (dw) m^{-2} d^{-1} and 12 g (dw) m^{-2} d^{-1}, respectively, were attained (Drysdale, Hanford et al. 1999). Initial work on the use of algae for gas exchange and food production has also shown promise (Fry, Hrabeta et al. 1987; Nakhost, Karel et al. 1987; Oguchi, Otsubo et al. 1987; Holtzapple, Little et al. 1989; Holtzapple, Little et al. 1989), though there has not been much follow up work during the last decade. The potential of producing food by growing yeast on chemically synthesized feedstocks was also studied during the late 1980's (Petersen, Stokes et al. 1983; Petersen 1988), but further research has not followed up here either. During the last decade, the initial work done under the CELSS program has been followed by the Advanced Life Support (ALS) program, which has focused on higher-plants almost exclusively.

Microbial food production, however, shows great promise for manned missions to Mars. Algal food can be produced at very high yields compared to higher plants, and also exhibits higher productivity. Algae, typically, are characterized as a high protein food with a high vitamin and mineral content. The harvest index (the ratio of edible biomass to inedible biomass) of algae is higher than most higher-plant crops. Yeast, too, also exhibits high yields and productivity. Yeast is also a high protein food with a good amino acid profile. Yeast can be grown in fermentors on chemicals easily synthesized from the Martian atmosphere. The potential yields and productivity of both yeast and algae compare favorably with higher plants. Furthermore, both algae and yeast can be grown by automated photobioreactors or fermentors. Both algae and yeast can at least partially recycle the inedible, unused biomass to improve overall system efficiency. Finally, both algae and yeast can be manipulated genetically for the purposes of producing a better food source.

There is a precedent for the use of microbial food. Many indigenous peoples have harvested and eaten algae. Spanish conquistadors recorded the preparation and consumption of algae by the Aztecs. People today living near alkaline lakes in Chad prepare a traditional food called "dihe" from harvested *Spirulina* to supplement their meals with protein and vitamins. Algae, and especially *Spirulina*, have been suggested as a candidate for Single-Cell Protein (SCP) improve poor diets in much of the world. Today, *Spirulina*, and other algae are sold as health supplements in much of the industrialized world. Yeast is also a familiar food product, being added to food as a protein supplement or natural flavor. Yeast has at times substituted for a significant portion of the diet as was the case following both world wars in Germany (Rose 1981).

The current reference manned missions to Mars (Drysdale, Maxwell et al. 1999) call for either a single crew (Reference Mission version 3.0), or a succession of crews (the Split-Mission variation) to deliver modules to establish a habitat near the Martian equator. The entire crew returns to Earth at the end of each mission, leaving behind their module and equipment. In the case of the Split-Mission variation, this module becomes part of the expanding habitat for subsequent crews. Food production in all proposed missions will rely either completely on earth-supplied foods or on a combination of shipped food and *in situ* production of high yield crops. However, there are certain inherent inefficiencies as well as dangers with these approaches. For example, in the case where higher-plants are grown, a new crop cycle must be initiated for each successive mission. Either mature food producing plants (as well as the biomass chamber equipment) need to be carried from Earth so that food is supplied both in transit and upon arrival or the mission must rely on stored food in transit and start new food production upon arrival. In the first scenario, launch and landing parameters must accommodate the weight of the plants, the production equipment, and extra water weight. In the second scenario, extra stored food must be supplied until crops reach maturity and food harvesting is possible. Futhermore, in either scenario, the crew’s welfare and mission success is dependent on a successful crop. One failed crop could end the mission and jeopardize the crew. In all variations of the reference mission, however, food supply represents a significant portion of IMLEO.

The solution proposed in this report is to produce and stockpile food using automated production units on Mars ahead of the crew’s arrival. This approach not only drastically cuts IMLEO launch costs, but also increases crew safety since a manned mission would not be sent to Mars uless sufficient food was stored to ensure their survival until they could return to Earth. Food depots, of course, have been used to great success throughout the history of human exploration, especially in Antarctic exploration, but this is the first time they would be used in space exploration. The establishment of food stockpiles on Mars necessitates the use of systems simple enough to be completely automated with minimal remote input. For this reason, growing higher plants would not be feasible. Managing two years of multiple crop cycles, harvesting, processing, and storing the food would require advanced robotics, prone to software and mechanical failure. Microbial food production is much more amenable to the proposed scenario. Here on Earth, modern breweries are completely automated and can run year-round shutting down briefly for minimal maintenance. Fermentor and algae production technologies are well advanced and tested. Automated monitoring of productivity and culture health is possible with routine industrial technologies. Automated harvesting and processing can be as simple (as in the case of the algae *Spirulina maxima*) as filtering the media to produce a slurry of 10% algae, and then freezing. Microbial food offers many advantages in Martian exploration, and perhaps the only means to establish a self-sustaining colony. Higher-plant crops and aquaculture production will play an important role in a self-sustaining colony, of course. Because microbial food production and stockpiling will allow crews to stay for extended periods, and be relieved by subsequent crews, on-going higher-plant crop production will allow the colony crew to diversify their diet to include the more traditional vegetables, tubers, and cereals as well as shellfish and fish from aquaculture production.

There are problems associated with microbial food production. The produced food would need to be a complete food from a nutritional standpoint. It must contain sufficient protein (with the proper amounts of all essential amino acids). It must contain sufficient carbohydrates that can be digested by humans to meet their energy needs. It must contain sufficient lipids (especially the essential fatty acids linoleic and linolenic acids). Finally, it must contain adequate vitamins and minerals to augment what won't be brought by the crew or resupplied. Microbial food is often seen as being high in protein, but low in usable carbohydrates and fats. Similarly, several studies have cited low digestibility, abdominal distress, and nucleic acid toxicity leading to joint pain and gout (Becker 1994). Several authors have stated that algae or yeast most likely could not be used as a complete food (Becker 1994; Vonshak, 1998). Current maximum daily intake of *Spirulina* as recommended by the U.N. Protein Advisory Group is 2g/day. This recommendation is based solely on nucleic acid toxicity. Other authors cite taste and palatability as reasons for limiting algae or yeast as a sole source of food (Holtzapple, Little et al. 1989). However, there is little actual data concerning high-percentage algae or yeast diets in humans. The basis for nucleic acid toxicity is well established, for example, but does not exclude microbial food if processing can remove the nucleic acids. Even without processing, it has been shown that rats can eat up to 30% of their diet in Spirulina with no ill effects (Salazar, Martinez et al. 1998; Chamorro and Salazar 1999) (higher percentages weren't studied). Moreover, several studies have shown that altering the growth conditions of algae or yeast can significantly alter their nutritional profile. More extensive studies need to be done to elucidate the potential of microbes as a sole food source.

The processing of both yeast and algae has also advanced greatly in recent years. Today, yeast is added to foods to increase protein content, but also to alter its flavor. Many different strains of yeast are grown to add a wide variety of flavors to food. Whereas *Spirulina* and other algae once had a unpleasant odor and taste, today *Spirulina* is quite mild in taste. New processing techniques such as processing with supercritical CO2 promise to make *Spirulina* even more acceptable to the human palette (Nakhost, Karel et al. 1987; Qiuhui 1999).

Finally, advances in biotechnology promise great improvements in microbial food quality. For example, the yeast genome *S. cereversiae* has been completely sequenced and other microbial genomes will hopefully soon follow such as *Candida utilis* , *Spirulina maxima* , *and Spirulina platensis* . Also, new techniques for the genetic engineering of these organisms are introduced on an on-going basis. The combination of genomic sequencing and new molecular techniques will greatly accelerate the engineering of these organisms. Already, some researchers are inserting entire metabolic pathways into yeast (Shimada, Kondo et al. 1998) to improve nutritional quality. It is even possible that a suitable yeast species and suitable algae species may be engineered in tandem to create a binary foodstuff. That is to say, the yeast's nutritional deficits will be complemented by the algae and vice versa. Such a system might allow the expression of enzymes in one organism to degrade the harmful or indigestible content of the other species, and vice versa. The possibilities of using microbial food for manned exploration of Mars are better than ever.

4.7.2. Phase I: Unmanned Food Production and Stockpiling

The automated food production and processing unit is to be emplaced in one of the ice caves peripheral to the main reactor. This location presents ideal opportunities for food production. First, the space is thermally insulated by the surrounding ice. If the average temperature of the cave is just below 0 C, the actual food production unit itself will not require much thermal insulation to maintain the culture growing temperature of about 35 C. Second, the thirty meters of ice above the ice cave shields the unit from radiation. While the effect of high radiation on yeast or algae is not well understood, less radiation exposure certainly lowers the mutation rate and lowers the risk of culture phenotypic drift over time. Third, the raw materials present in the surrounding ice and Martian atmosphere allow microbial food growth with minimal supplies brought from earth (Table 1). Water is plentiful. Carbon dioxide composes over 95% of the Martian atmosphere. The CO_2 can be used directly by algae, or can serve as a substrate for chemical reactions to produce simple hydrocarbons and alcohols that are used as feedstock for yeast production.

Table 1 Composition of the Martian Atmosphere

Component	Percentage (by Volume)
Carbon Dioxide (CO_2)	95.32
Nitrogen (N_2)	2.7
Argon (Ar)	1.6
Oxygen (O_2)	0.13
Carbon Monoxide (CO)	0.07
Water Vapor (H_2O)	0.03

Source: Drysdale *et al*, 1999

Atmospheric nitrogen, while composing only 2.7% of the Martian atmosphere, can be concentrated for use by N_2-fixing algae, or production of ammonia for use in algae and yeast production. Certain minerals and trace elements will need to be transported from Earth. The minerals that constitute the bulk of this requirement contain Sodium, Potassium, and Phosphorous, Calcium, Iron and others will only represent 2-8% of the final biomass.

The under-ice environment also allows processed food to be stored in auxiliary caves at temperatures less than 0 /C. Thus, after preliminary crude processing by the automated unit, frozen algae or yeast can be stored in brick-form indefinitely, or frozen in ice pits. Many tons of microbial food can thus be stockpiled before the crew's arrival. Indeed, even a small fraction (less than 10%) of the power generated by a 5MW(t)/1MW(e) nuclear reactor and directed towards food production and processing can generate vast quantities of food. Assuming a system with 1% efficiency overall at converting electrical power into edible algal biomass, operating over a two year period, it is possible generate years of food supply before the crew even arrives. This large supply of food could easily be stored in below-freezing ice-caves.

Selection of organisms for food production for the unmanned mission requires careful study. Many different organisms have been studied as candidates for single-cell protein production on earth (Israelidis, 2000). Two methylotropic bacteria, *Acinetobacter* and *Flavobacterium* were studied by Shell Oil for producing SCP from methane. ICI developed a product named Pruteen from *Methylophilus methyltropha* grown on methanol. Burns-Phillip sells a product today named Torula made from yeast grown on ethanol. Several different genuses of microalgae have been studied for food production on earth and in space. Most notably these include, *Chlorella, Scendemonas* and *Spirulina* . This report considers only two of all these candidates: yeast (of which the most promising is *Candida utilis*) and *Spirulina*. These two candidates have been the subject of much research. Their extracts are already on the Food and Drug Administration's GRAS (Generally Regarded as Safe) list. They are amenable to automated production and produce high yields. The next sections will examine these candidates in detail.

4.7.3. Spirulina

Nutritional Value

Worldwide production of *Spirulina* is currently about 2500 tons (Borowitzka 1999) most of which is devoted to the nutritional supplement market. Spirulina is a high protein, high vitamin and high mineral food. Its gross chemical composition (Table 2) is dominated by protein, which is often as high as 65%. The amino acid profile of *Spirulina* -based protein (Table 3) contains all the essential amino acids, and although the data vary from study to study, most authors conclude that *Spirulina* is deficient (on a percentage basis) only in the sulfur-containing amino acids, cysteine and methionine (Lembi and Waaland 1988). Several studies have summarized *Spirulina* protein quality using such standard nutrion concepts as Net Protein Utilization (NPU), Biological Value (BV), and Protein Efficiency Ratio (PER). According to Jasby (Lembi and Waaland 1988), the usable protein (the product of NPU and total protein) of *Spirulina* placed it below poultry and fish, about equal with meat and dairy, and above all plant protein sources (table 4).

As is seen in Table 2, the carbohydrate content of *Spirulina* is around 10-20%. This is below the 30-50% range recommended for human nutrition (Shils, Olson et al. 1994; Eastwood 1997). The major neutral sugars in *Spirulina* are glucose and galactose, composing over 80% of neutral sugars, implying high digestibility of *Spirulina* carbohydrate. While some authors (Quillet, 1975; Santillan, 1982) found that the major sugar was rhamnose, others (Casu, 1990) found that the majority of carbohydrate was glycogen. The most likely explanation for the variation lies in strain selection and growth conditions. Spirulina is rare among algae in that it does not have an indigestible cell wall like *Chlorella* and others. It's cell wall is made of digestible mucopolysaccharides.

Table 2 Chemical Composition (g 100 g^{-1} dw) of *Spirulina maxima*

Water	7.2
Ash	7.3
Carbohydrates	12.6
Lipids	6.4
Protein	68.9
Nucleic Acids	5.7
Chlorophyll a	0.90

Table 3 Amino acid profile of *Spirulina maxima*

Amino Acid	g/16g N
Asp	11.2
Glu	10.7
Ser	5.5
Gly	6.0
Arg	10.0
Ala	8.9
Pro	4.4
Hys	1.7
Tre	6.1
Tyr	7.3
Phe	1.3
Val	8.4
Met	2.0
Cys	0.6
Ile	4.2
Leu	5.5
Lys	6.1

Source: Ortega-Calvo and Mazeulos, 1993

Table 4 Comparison of protein quality and quantity for *Spirulina* and other foods

Food group	NPU (%)	Total Protein (%fw)	Usable protein (%fw)	Total protein (%dw)	Usable protein (%dw)
Spirulina	46-63	63	29-40	66	30-42
Dairy (Parmesan cheese)	70	36	25	51	36
Poultry (turkey, roasted slices)	70	31	22	81	57
Legumes (Soybeans)	61	34	21	38	23
Seafood (tuna, canned, drained)	80	24	19	62	50
Meat (pork loin, broiled, medium fat)	67	29	19	54	36
Nuts and seeds (pine)	50	32	16	34	17
Grains (hard red spring wheat)	60	14	8	16	10
Vegetables (broccoli)	<60	4	<3	38	<24

Source: Lembi and Waaland, 1988

Lipid content is also low in *Spirulina*, between 5 and 10 percent. Most sources indicate that the human diet should contain between 10 and 30 percent lipid overall (Shils, Olson et al. 1994). Some studies have reported higher dry-weight lipid contents of 16%. As with carbohydrate content, lipid content probably is highly dependent of strain selection and growth conditions. Most of this fat is burned by the body for energy, but some serve to maintain the body's fat reserves, structural components such as cell membranes and other functions. The body can manufacture almost all the lipids it needs from simple sugars except for the essential fatty acids (EFAs), linoleic and linolenic acids. Fortunately, *Spirulina* produces up to 16% of its total fatty acids as linolenic acid (Ortega-Calvo, Mazuelos et al. 1993). Unfortunately, *Spirulina* appears to be deficient in linoleic acid, and this deficit will need to be addressed wither through supplements or genetic modification of *Spirulina* .

As already mentioned, growth conditions can alter the nutritional profile of *Spirulina* dramatically. For example, Fry (Fry, Hrabeta et al. 1987) found that they could markedly increase the glycogen content of another algae, *Synechococcus* , from 1% to 35% by growing the cells below 20 /C. Similar manipulation of *Spirulina* composition may be possible with relatively simple alterations to growing conditions. In another study, it was shown that the lipid content of *Spirulina* could be manipulated by growing the cells mixotrophically (Durand-Chastel 1999). Varying the salinity levels can also change *Spirulina* composition by decreasing protein content and increasing carbohydrate content to over 60 percent (Vonshak 1998) .Another possibility is using periods of light and dark to mainpulate compostion. The ability to precisely control growth conditions is an advantage of compact photobioreactors as compared to open growing systems. Further studies are needed to elucidate how much *Spirulina* can be manipulated in this way in order to make a better food supply.

Toxicology Studies.

The most common toxin associated with *Spirulina* is nucleic acid. Compared with other algae, *Spirulina* has a relatively low nucleic acid content of about 4%. Since the United Nations Protein Advisory Group has recommended that nucleic acid intake be limited to 2g d^{-1}, this would limit dry weight *Spirulina* intake to 50 g d^{-1}, or approximately 10% of a typical daily diet. Nucleic acids can be removed by processing in alkaline solutions (NaOH), high salt, or enzymatically (DNase and RNase), thus leading to much lower toxicity. Other potential toxic effects of algae-based food, include allergins, biogenic toxins from intruding, opportunistic species, and heavy metal accumulation. While allergins still need further study, biogenic toxins and heavy metal accumulation appears to be a problem associated with open pond production instead of the highly controlled closed photobioreactor approach proposed here. Furthermore, very few studies of *Spirulina* toxicity have been undertaken in humans. In rats, it has been shown that unprocessed, spray-dried *Spirulina* can be substituted for 10, 20 or 30% percent of the diet with no discernible toxic effect (Chamorro and Salazar 1999). Higher percentages in the diet were not studied.

Spirulina processing

Simplicity is the key objective for food processing in the proposed unmanned mission. To that end, it makes sense to minimally process the algae, and store it, until the crew arrives. *Spirulina*, fortunately, is simple to process. It is sufficiently large for cultures to be strained or concentrated by filters. Indeed, village-based cultivation often harvests *Spirulina* with cheesecloth. For the proposed mission, the compact cylindrical photobioreactor can concentrate the algae until it is slurry of 10% algae. The algae can then be frozen in brick molds and stored without degradation in nutritional value. Or, the slurry can be poured into ice-pits and frozen. When the crew arrives they can thaw the slurry at their convenience to complete the processing. Further processing would include complete drying. Of the three methods common on Earth (sun-drying, spray-drying and drum-drying) drum drying appears to be the most simple, and the one the preserves the algae's nutritional quality best. Other processing, would include nucleic acid extraction (Nakhost, Karel et al. 1987), carbohydrate and lipid concentration, and possibly extraction with supercritical CO_2 to remove odor and unpleasant flavor (Nakhost, Karel et al. 1987; Qiuhui 1999).

Spirulina nutrition

Almost 98% of the elemental composition of *Spirulina* (Table 5) can be supplied through processing either the Martian atmosphere or Martian water. This includes *Spirulina* 's requirement for CO_2, O_2, H_2O, and a source of Nitrogen (whether it be N_2, NH_3, or NO_3). Other macronutrients, including S, P, Na, K, Mg, and Ca might be supplied using Martian resources, but could be brought from earth if necessary. The remaining micronutrients (Fe, Mn, Zn, B, Cu, Ni, Co, Cr, Mo, V and Ti) represent so small a proportion of the whole that they could easily be supplied from Earth.

Table 5 Element Composition of *Spirulina maxima*

Element	(g 100 g^{-1} ash free dw)
C	53.45
H	7.62
O	25.51
N	12.45
S	0.97

Source: Ortega-Calvo and Mazuelos, 1993

Photobioreactors

Many different technologies have been employed to grow *Spirulina* on earth. The simplest has been the use of shallow open ponds or raceways circulated with paddle wheels. These open systems are subject to environmental variations, varying nutrient levels, and contamination with alien algae. Closed bioreactors have been used to combat some of these problems. Horizontal tubular and flat-plate bioreactors (Borowitzka, 1984) often exhibit higher productivity than open systems and the risk of contamination is low. Closed systems are considered to be superior for growing algae to produce high-value nutritional supplements and pharmaceutical products. These systems most often are located outdoors to use sunlight. Potential problems with closed systems include hydrodynamic problems due to the high viscosity of the filamentous *Spirulina*. However, tubular photobioreactors with an internal diameter of only 2.5cm have been shown to operate efficiently with very high productivities (Vonshak 1998). Finally, compact photobioreactors have been designed with internal light sources. Typically, these consist of a cylindrical reaction chamber with inlets for media and gases, and outlets for harvesting. The algae mixture is stirred continuously to minimize self-shading of the algae. The light source is often simply a fluorescent bulb, but a more advanced system using thin-film, highly efficient Organic LEDs (OLEDs) could cover all interior surfaces to maximize light utilization.

These closed system designs allow easy control of growth conditions, including light, temperature, algae concentration and media composition. Since the algae are constantly stirred the average cell is exposed to more light unlike some systems where self-shading is a problem. These systems are characterized by high productivity, but are difficult to scale up to industrial levels. However, a 125 L photobioreactor producing 1g (dry-weight) L^{-1} hr^{-1} would produce over 2 metric tons of dried algae over the proposed two year period.

Efficiency, productivity and yield

There are two processes in particular whose efficiencies limit the systems overall efficiency: lighting efficiency and photosynthetic efficiency. Inefficient incandescent lighting or fluorescent lighting is typically used for small earth-based applications. Higher-efficiency technologies such sodium vapor-phase lights have also been used. The most promising technologies, however, are LEDs or organic LEDs (OLED) with technologies whose efficiencies are approaching 40%. LED technologies also have the advantage of producing very little heat. Thus, cooling the medium to remove excess heat would not be necessary. These technologies work well with *Spirulina* photosynthesis because *Spirulina* requires only red light, unlike higher plants that grow best under a mixture of red and blue light. *Spirulina* photosynthetic efficiency is calculated by the yield of biomass per kcal of light energy absorbed. In the case of *Spirulina*, the yield has been estimated to be 0.01-0.02 g $kcal^{-1}$, or 6-12% (Radmer, Cox et al. 1987; Vonshak 1998). Radmer states that algae have a maximum efficiency of 20% under sunlight, but their relative efficiency can be increased to 30% using monochromatic light. This increased efficiency implies a maximum yield of 0.05 g $kcal^{-1}$. A photobioreactor using red OLEDs would seem ideal, then, for the proposed mission.

Advances in genetic engineering of *Spirulina*

Very little work has been done on the genetic manipulation and engineering of *Spirulina* compared to other organisms, but this is now beginning to change. There are several technical reasons why Spirulina is a difficult organism to manipulate. Vonshak (1997) has listed several: first, the difficulty of growing completely bacterial-free cultures; second, *Spirulina* exhibits very high endonuclease and exonuclease activity, which is a barrier to foreign DNA introduction; third, endogenous plasmids that could be useful in genetic transfer are not yet available.

However, some researchers have had success in creating genomic libraries, the first step to whole genome sequencing and individual gene cloning, for *Spirulina* (Kawata, Yano et al. 1998) There have also been many successes in cloning individual *Spirulina* genes (Vachhani and Vonshak 1996; Kawata, Yano et al. 1998). Progress has also been made on the problems of nuclease activity and gene transfer. Some researchers (Cao, Xu et al. 1999) have been able to grow *Spirulina* in Mg^{2+}-free media, which significantly inhibits endogenous DNase activity. There have also been reports of plasmids in *Spirulina*, but more work needs to be done in this area.

There are challenges to engineering *Spirulina*, but these challenges will hopefully yield to the increasing knowledge and technological sophistication of biotechnology.

4.7.4 Yeast

Yeast also shows promise for automated food production during the unmanned mission. There are several species of yeast approved for human consumption in the United States, including *Saccharomyces cerevisiae*, *Candida lypolitica* , *Kluyveromyces fragilis*, and *Candida utilis* . The yeast *C*. *utilis* is particularly promising since it can be grown on ethanol and has been used for the industrial production of protein (autolysed yeast) and natural flavorings.

Like *Spirulina*, under normal growing conditions yeast is high in protein (greater than 50%) and comparatively low in carbohydrates and lipids. Like *Spirulina*, it is also deficient in the sulfur-containing amino acids, methionine and cysteine. When supplemented with these amino acids, yeast has the equivalent nutritional quality of soya cake or fish meal (Boze, Moulin et al. 1992).

While carbohydrate levels are normally lower than would be desired in most strains, *C*. *utilis* strains have been isolated that, when grown in a low nitrogen, ethanol based-media, produce carbohydrate at levels greater than 70% total carbohydrates and 50% edible carbohydrates. Similar results were obtained with other yeast grown on methanol (Petersen, Stokes et al. 1983; Petersen 1988).

One limitation to the use of yeast as a microbial food source is it's low production of lipids. While human nutrition requires between 10% and 30% lipids in the diet, yeast commonly are composed of only 5% lipid. The lipid profile also appears deficient in the essential fatty acids. This would be a serious drawback to using yeast as a single food source. While the proportion of edible biomass to inedible biomass is as high or higher than most plants, its low lipid content and low methionine and cysteine content need to be addressed.

Another problem with yeast is the high nucleic acid content. Whereas *Spirulina* typically has a 4% nucleic acid content, yeast average 12%-16% nucleic acid content. The most successful technique for reducing nucleic acid content appears to be sodium hydroxide treatment which reduces the nucleic acid content of yeast grown on gas-oil 75% for RNA and 81% for DNA. Even with these reductions, to be able to stay within the 2 g d^{-1} limit a maximum of only 62g dried yeast could be eaten. More efficient methods for removing nucleic acids must be found for yeast to be a safe and practical food source, such as enzymatic digestion of nucleic acids using DNases and RNases.

Despite this yeast has at times constituted significant portions of the human diet. After WW I, and WW II, the German people ate yeast to supplement their protein levels. Four yeasts have been added to the GRAS (Generally Regarded as Safe) list and approved as a food ingredient by the US FDA: *S. cerevesiea, C. lipolytica, C utilis, and K. fragilis* (Boze, Moulin et al. 1992). Furthermore, yeast has a harvest index of over 50%, which compares favorably to most plants. Yeast is easily processed into a dried powder, flake or cake form, though it can be stored as frozen concentrated slurry, as is the case with algae.

Unlike algae, yeast don't require light and can be grown in media containing either hydrocarbons or alcohols, synthesized from *in situ* materials as the main carbon source. This simplifies the design of the automated food production unit to a certain degree. Unfortunately, only 92%-94% of yeast's elemental content can be supplied by the Martian atmosphere and ice alone (C, H, N, O). Macronutrients and micronutrients constitute 6%-8% of yeast and would need to be supplied from Earth (Table 6). This requirement might be decreased if the yeast are processed to separate edible and inedible biomass, and then the inedible biomass is recycled through the fermentors, but this would increase the complexity of the system, and might not be sufficiently reliable for automated production.

One advantage of yeast over algal-based food is that yeast exhibits much higher productivities (Table 7). They also exhibit high yields. Provided that the carbon, nitrogen and oxygen substrates can be produced efficiently, yeast may be produced in such abundance that harvesting only a small, highly desirable fraction of the yeast biomass may be worthwhile.

Perhaps the major advantage of yeast is the ease with which it is genetically engineered. Yeast is a cornerstone of modern molecular biology and biotechnology. The yeast Saccharomyces cerevisiae was the first eukaryotic organism whose genome has been completely sequenced. Many methods of introducing new genetic material into yeast are in use today, as well as techniques for controlling expression of introduced genes. Entire metabolic pathways have been inserted into yeast for the production of nutritional supplements, chemicals or pharmaceuticals. One group (Shimada, Kondo et al. 1998) introduced several carotenoid genes into yeast in order to produce high levels of lycopene. While it is unclear whether yeast can be engineered to be a complete food by itself, it shows great promise in supplying the nutrients that can't be supplied by algae alone.

Table 6 Element Composition of *Candida*

Major Elements (%)	
C	45.94
H	6.72
N	7.31
O	32.08
Major minerals (%)	
Ca	0.57
Fe	0.01
Mg	0.13
P	1.68
K	1.88
Na	0.01
Trace elements (μg g^{-1})	
Co	-
Cu	13.4
Mn	38.7
Zn	99.2

Source: Boze *et al*, 1992

Table 7 Yields and productivities of yeast grown on different substrates

Substrate	Organism	Yield (g g^{-1})	Productivity (g h^{-1} L^{-1})
Methanol	*Pichia pastoris*	0.40	11.6
Ethanol	*C. ethanothermophylum*	0.95	1.6
n-Alkane	*C. lipolytica*	0.88	3.78

Source: Boze *et al*, 1992

4.7.5 Phase I summary

From a food production standpoint, the goal of the unmanned mission is to produce and stockpile a two-year supply of food for the six-member crew of manned mission over a two-year period. Another way of looking at this is that the unmanned mission produces enough food on a daily basis to feed a six-man crew for one day. This goal is somewhat arbitrary and depends on the level of risk acceptable to mission planners. For example, if the newly arrived crew finds that their return vehicle is damaged, or their plant-based life support system is nonfunctional, how much food should be available to ensure survival while they wait to return to Earth. The nutritional goals for this food stockpile include a 3000 kcal d^{-1} diet for each of the six crew, with a nutritional composition of 50% carbohydrate, 30% fat, and 20% protein. The daily food supply should also not contain any toxins, be easily digestible, and be amenable to modification in flavor and texture through simple cooking practices. Algae, and possibly yeast, are good candidates to fulfill these requirements. It is clear that possible genetic engineering, growth conditions modifications and food processing would be needed to produce a final product that met these criteria. For example, even after genetic engineering and growth conditions modification it might be necessary to process the algae or yeast to enrich the end product for higher fat content. Likewise nucleic acid removal might degrade nutritional quality.

For the purposes of this paper, and for the preliminary calculations of a automated food production unit's energy and mass budget, we make the following assumptions: first, the final harvest index for a microbial food source yielding a complete or nearly complete food would be between 25% and 50%; second, productivities for algae production would range from 0.25 to 1 g l^{-1} hr^{-1}, and for yeast would range from 1 to 5 g l^{-1} hr^{-1}; third, energy efficiencies of at least 10% to 50% could be achieved in the production of light from electricity (in the case of algae) or the production of substrate from *in situ* materials (in the case of yeast); fourth, yields for algae production would range from .002 to .008 g $kcal^{-1}$ light energy, where as yields for yeast would range from 0.5 to 0.8 g g^{-1} carbon based feed stock (either ethanol or methanol). Not factored into these preliminary calculations is the energy and mass costs of providing CO_2 and a nitrogen source (whether it be N_2 or NH_3 or $^-NO_3$) to algae, or the costs of supplying O_2 to yeast). It is assumed that nuclear reactor has sufficient power to allow the production of these substrates. Finally, the mass and energy limits allocated for automated food production for the unmanned mission overall are estimated to be 500 kg IMLEO and 100 kW (10% of reactor electricity generation) respectively.

Given these constraints, it is possible to design an system that would supply adequate food. Table 8 details the volumetric requirements of such a system given the range of productivities and harvest indexes. Table 9 details the maximum mass of the system after accounting for the mass of macronutrients needed for growth media. Since the largest system (an algal system) requires 1000 L capacity (or 1 m^3) it seems possible to design a complete system with a mass less than 464 kg. Finally, Table 10 outlines the energy requirements to produce the light for an algae system. In case of algae, energy requirements are much less than even 5% of the 100kW available indicating the total system energy costs will be far below the 100kW limit. This surplus energy, then, could be dedicated to other components of the unmanned mission.

4.7.6 Phase II: Manned Missions

As already mentioned, food production and stockpiling during the unmanned mission is not critical to the success of subsequent manned missions. In the reference mars mission (version 3.0), life support and food supply for a 600-day mission is already budgeted without the use of bioregenerative life support. These parameters could be adapted to the proposed Mars polar ice base with little change. Similarly, the current proposals for use of bioregenerative life support (based mostly on higher-plant production) in the reference mission (or with the Split-Mission or Extended Mission alternatives) could also apply to a Mars polar ice base. Even if traditional or recent ALS life-support systems are used instead of unmanned automated food production and stockpiling, the ice base scenario offers several advantages for food production and opportunities to reduce total system mass. First, since ice caves are easily created, insulated and pressurized, this current proposal allows for great increases in available growing area with little or no increase in total system mass. All of the crops proposed for use in ALS (Table 11) could be grown in ice caves. In the current reference mission, habitat module mass and size dictate growing area,

Table 8 Growth chamber volume requirements (L) for automated food production for given productivities and harvest fractions

	Spirulina		Yeast	
	0.5 g L^{-1} h^{-1}	1.0 g L^{-1} h^{-1}	1.0 g L^{-1} h^{-1}	5.0 g L^{-1} h^{-1}
Harvest Index				
50%	500	250	250	50
25%	1000	500	500	100

Table 9 Mass budget for automated food production

	Spirulina	Yeast
Fraction of food product not supplied by Martian resources	2%	8%
Macro- and micronutrients supplied from Earth	36 kg	144 kg
Maximum mass of balance of system	464 kg	356kg
Total	500 kg	500kg

Table 10 Energy requirements for lighting in automated *Spirulina* production[a]

Photosynthetic efficiency[b]	
0.002	1380 W
0.008	340 W

a. Assumes 50% efficiency in converting electricity to light. Also assumes a daily production of 18,000 kcal food energy after processing (50% harvest index)
b. Grams of biomass produced per kcal of light absorbed (g $kcal^{-1}$)

Table 11 Crops proposed for use in ALS

Soybean	Wheat	White Potato
Sweet Potato	Rice	Peanut
Carrot	Cabbage	Lettuce
Dry Bean	Celery	Green Onion
Strawberry	Peppers	Pea
Mushroom	Snap Bean	Spinach
Tomato		

Source: Drysdale *et al*, 1999

thus mandating the need for extremely high crop productivity. The ice base approach allows growing of crops with more traditional, tested methods. Additionally, ice-caves with the appropriate insulation and lining can be turned into high-volume ponds for aquaculture and fish farming, which would be impossible in any other Mars scenario.

However, establishing unmanned food production and stockpiling makes sense for two reasons. Most importantly, having a large food cache already positioned before the first manned mission departs for Mars adds to the crew's safety. As outlined in Reference Mission version 3.0, contingencies should be made for food supply if a crew must delay their planned return to Earth. Opportunities for Earth-Mars transit using reference mission vehicles occur once every 22 months, which is why an extra 600-day food supply should be added as a contingency. In this paper, it is proposed that a 600 day food supply be established on Mars before the crew departs Earth, which means that even if food production machinery fails catastrophically the day the crew leaves Earth they will have enough food supply to see them through the mission. Of course, so long as food production machinery remains working, they will not decrease the food stockpile since food production and consumption will be equal in the proposed system. Indeed, the food stockpile could be increased after the crew arrives since the crew could bring additional photobioreactors or fermentors and will also have started hydroponics and aquaculture.

Growing the food stockpile will allow the establishment of a bigger ice base with more crew.

Another reason for pursuing microbial food production is that algae or yeast are most likely the most efficiently produced food in terms of total mass, energy usage and crew time. Being lowest on the food chain, algae allow more efficient production of shellfish and fish in aquaculture. It remains to be seen whether culture of fish such as *Tilipia* can be sustained solely on algae, but is known that other aquaculture feed (such as rotifers) can be grown on algae. Any attempt at Martian aquaculture will most certainly require the production of algae.

Food production for a self-sustaining colony will be much easier in an ice base scenario than in any other due to abundant power, water, manufactured air supply, inherent radiation shelter, insulation properties, and the feasibility of large growth chambers. However, some challenges would need to be overcome: recycling of nutrients. Nutrients such as Na, K, P, Ca, S, Fe, etc. would most likely need to be recycled with a high degree of closure. Unless these nutrients can be refined from dust trapped in the ice cap, or obtained by sorties to areas with Martian soil, these nutrients will need to be brought from Earth and recycled very efficiently. As the total biomass of the colony grows with increasing crew size, the importation of these nutrients must be increased accordingly.

4.7.7 Conclusions

The purpose of this report is to summarize the advantages of producing food at the Martian North Pole, provide a rough estimation of energy and mass requirements for such activity, and point out what technical challenges remain to be overcome. Automated production of a algae or yeast based food supply by an unmanned mission offers many advantages. Such a strategy could drastically reduce IMLEO as well as provide extra food security to the crews that arrive at the ice-base.

The two most promising candidates for unmanned food production are *Spirulina* and yeast. Since both are produced industrially on Earth, by largely automated processes, for human consumption, these candidates are already the subject of much research. The fact that they haven't been engineered to be a complete food source might be more a matter of economics and market demand than any inherent intractable problems. *Spirulina* and yeast could make possible not only cheaper and safer exploration of Mars, but also the establishment of a large self-sustaining colony.

Several technical challenges need to be overcome however before this approach can succeed:

- Nutritional profiles under all growing conditions for both candidates need to be ascertained.

- More complete toxicological studies need to be done.
- Food processing techniques to increase palatability need to be explored
- Photobioreactor and fermentor design must be optimized to maximize productivity and yield while remaining reliable
- Development of new techniques for the genetic engineering of *Spirulina*.

These problems are not intractable, but they do require a serious, integrated research effort. Overcoming such challenges, however, would be not only be significant to the exploration of Mars, but also would yield additional benefits on Earth. For example, *Spirulina* holds great promise as a means to fight malnutrition and famine if it could be engineered to be a complete food. Finally, the success of a Martian polar mission is not dependent upon the development of unmanned food production, but such development would lead to much lower IMLEO overall, more quickly allow the establishment of self-sustaining colonies, and increase the food security of the crew.

Bibliography

1. Abou-Zeid, A.-Z. A., J. A. Khan, et al. (1995). “On Methods for Reduction of Nucleic Acids Content in a Single-Cell Protein from Gas-Oil.” Bioresource Technology **52**: 21-24.
2. Adeogba, S. and M. H. Bernstein (1998). “Effects of dietary Spirulina on weight, food intake, and metabolism in rats.” FASEB Journal **12**(4): A561.
3. Avault, J. W. (1996). Fundamentals of Aquaculture: A Step-by-Step Guide to Commercial Aquaculture. Baton Rouge, AVA Publishing Company Inc.
4. Bagherpour, S. and P. Sperrazzo (1998). “Comparison of spirulina growth in a tubular bioreactor and an open raceway pond.” Journal of Phycology **34**(3 SUPPL.): 4-5.
5. Baquerisse, D., S. Nouals, et al. (1999). “Modelling of a continuous pilot photobioreactor for microalgae production.” Journal of Biotechnology **70**(1-3): 335-342.
6. Becker, E. W. (1994). Microalgae: Biotechnology and Microbiology. Cambridge, Cambridge University Press.
7. Blackwell, A. L. and C. C. Blackwell (1990). No.90CH2896-9), San Diego, CA, USA, American Autom. Control Council.
8. Bonnin, G. (1993). “A scheme for the transfer of technology concerning Spirulina production and utilization to developing countries.” Bulletin de l'Institut Oceanographique (Monaco) **0**(SPEC. ISSUE 12): 157-167.
9. Borowitzka, M. A. (1999). “Commercial production of microalgae: Ponds, tanks, tubes and fermenters.” Journal of Biotechnology **70**(1-3): 313-321.
10. Borowitzka, M. A. (1999). “Commercial-scale culture of Cyanobacteria.” Bulletin de l'Institut Oceanographique (Monaco) **19**(special issue): 507-515.
11. Borowitzka, M. A. and L. J. Borowitzka, Eds. (1988). Micro-Algal Biotechnology. Cambridge, Cambridge University Press.

12. Boze, H., G. Moulin, et al. (1992). “Production of Food and Fodder Yeasts.” Critical Reviews in Biotechnology **12**(1/2): 65-86.
13. Brahamsha, B. (1999). “Genetic manipulations in Synechoccus spp. of marine cluster A.” Bulletin de l'Institut Oceanographique (Monaco) **19**(special issue): 517-527.
14. Campanella, L., G. Crescentini, et al. (1999). “Chemical composition and nutritional evaluation of some natural and commercial food products based on Spirulina.” Analusis **27**(6): 533-540.
15. Campanella, L., G. Crescentini, et al. (1998). “Determination of macrominerals and trace elements in the alga Spirulina platensis.” Analusis **26**(5): 210-214.

Cao, J., Z. Xu, et al. (1999). “Studies on the sensitivity of Spirulina platensis to antibiotics and herbicide: Relationship with selectable markers for genetic transformation.” Bioresource Technology **70**(1): 89-93.

Cao, J., Z. Xu, et al. (1999). “Effects of Mg2+ on the growth and DNase activity of Spirulina platensis, a cyanobacterium.” Bioresource Technology **67**(3): 287-290.

Chamorro, G. A. and M. Salazar (1999). “Toxilogical evaluations of Spirulina maxima in rodents.” Bulletin de l'Institut Oceanographique (Monaco) **19**(special issue): 529-532.

Chanawongse, L., Y. K. Lee, et al. (1994). “Productivity of the cyanobacterium Spirulina platensis in cultures using sunlight.” Bioresource Technology **48**(2): 143-148.

Chien, L. F. and A. Vonshak (2000). “Cold acclimation of two strains of the cyanobacterium, Spirulina platensis.” Journal of Phycology **36**(3 Supplement): 12.

Coin, M. A., S. Bagherpour, et al. (2000). “Tube size comparison and automated growth measurement in a tubular reactor using Spirulina plantensis.” Journal of Phycology **36** (3 Supplement): 15.

De, O. M. A. C. L., M. P. C. Monteiro, et al. (1999). “Growth and chemical composition of Spirulina maxima and Spirulina platensis biomass at different temperatures.” Aquaculture International **7**(4): 261-275.

Deshnium, P., K. Paithoonrangsarid, et al. (2000). “Temperature-independent and -dependent expression of desaturase genes in filamentous cyanobacterium Spirulina platensis strain C1 (Arthrospira sp. PCC 9438).” FEMS Microbiology Letters **184**(2): 207-213.

Drysdale, A. E., A. J. Hanford, et al. (1999). Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document. Houston, Texas, NASA - Lyndon B. Johnson Space Center**:** 36.

Drysdale, A. E., S. Maxwell, et al. (1999). Advanced Life Support Systems and Analysis Reference
Missions Document. Houston, Texas, NASA - lyndon B. Johnson Space Center**:** 34.
Durand-Chastel, H. (1999). “Production of Spirulina biomass rich in gamma-linolenic acid and sulfolipids.” Bulletin de l'Institut Oceanographique (Monaco) **19**(special issue): 541-546.

Eastwood, m. (1997). Principles of Human Nutrition. London, Chapman & Hall.

Fox, R. D. (1983). Algoculture. Strasbourg, L'Universite Louis Pasteur de Strasbourg**:** 336.

Fox, R. D. (1999). “Third millenium aquaculture. Farming the micro-oceans.” Bulletin de l'Institut Oceanographique (Monaco) **0**(SPEC. ISSUE 19): 547-563.

Fry, I. V., J. Hrabeta, et al. (1987). “Application of Photosynthetic N2-Fixing Cyanobacteria to the CELSS Program.” Advances in Space Research **7**(4): 39-46.

Geeta, G. S. and P. K. Singh (2000). “Isolation and characterization of amino acid-analogue-resistant mutants of Spirulina platensis.” World Journal of Microbiology & Biotechnology **16**(4): 397-399.

Geider, R. J., Ed. (1992). Algal Photosynthesis. Current Phycology. Routledge, Chapman & Hall.

Gordillo, F. J. L., C. Jimenez, et al. (1998). “Effects of increased atmospheric CO2 and N supply on photosynthesis, growth and cell composition of the cyanobacterium Spirulina platensis (Arthrospira).” Journal of Applied Phycology **10**(5): 461-469.

Graham, L. E. and L. W. Wilcox (2000). Algae. Upper Saddle River, Prentice-Hall, Inc.

Holtzapple, M. T., F. E. Little, et al. (1989). “Analysis of an Algae-based CELSS. Part1: Model Development.” Acta Astronautica **19**(4): 353-364.

Holtzapple, M. T., F. E. Little, et al. (1989). “Analysis of an Algae-based CELSS. Part 2: Options and Weight Analysis.” Acta Astronautica **19**(4): 365-375.

Hurtl, H. V., R. A. Sacher, et al. (1990). Proceedings of the Fourth European Symposium on Life Sciences Research in Space (ESA SP-307), Trieste, Italy, ESA.

Israelidis, C. J. (2000). Nutrition - Single Cell Protein Twenty Years Later.

Joo, D.-S., M.-G. Cho, et al. (1998). “Growth and fatty acid composition with growth conditions for Spirulina platensis platensis.” Journal of the Korean Fisheries Society **31**(3):

409-416.

Joo, D.-S., M.-G. Cho, et al. (1998). “Lipid extraction from Spirulina platensis using supercritical carbon dioxide and analysis of fatty acid compositions in extracts.” Journal of the Korean Fisheries Society **31**(3): 417-422.

Kawata, Y., S. i. Yano, et al. (1998). “Construction of a genomic DNA library of Spirulina platensis and cloning carotenoid synthesis genes.” Plant and Cell Physiology **39**(SUPPL.): S84.

Kawata, Y., S. i. Yano, et al. (1998). “Construction of a genomic DNA library by TA cloning.” Biotechniques **24**(4): 564-565.

Knutsen, G. and K. Skjanes (1999). “Simple growth chambers for culturing microalgae with precision at different temperatures and irradiance.” Journal of Applied Phycology **11**(6): 487-491.

Lance, J. R. and J. W. H. Chi (1989). Space nuclear power systems for extraterrestrial basing. IAF International Conference on Space Power, Cleveland, OH, USA.

Lane, H. W., S. M. Smith, et al. (1994). “Nutrition in space: lessons from the past applied to the future.” American Journal of Clinical Nutrition **60**(supplement): 801S-5S.

Langdon, C. and E. Onal (1999). “Replacement of living microalgae with spray-dried diets for the marine mussel Mytilus galloprovincialis.” Aquaculture **180**(3-4): 283-294.

Lee, Y.-K. (1997). “Commercial production of microalgae in the Asia-Pacific rim.” Journal of Applied Phycology **9**(5): 403-411.

Lembi, C. A. and J. R. Waaland, Eds. (1988). Algae and Human Affairs. Cambridge, Cambridge University Press.

MacElroy, R. D. and J. Bredt (1984). “Current Concepts and Future Directions of CELSS.” Advances in Space Research **4**(12): 221-229.

Maeda-Martinez, A. M., H. Obregon-Barboza, et al. (1995). “Laboratory culture of fairy shrimps using baker's yeast as basic food in a flow-through system.” Hydrobiologia **298**(1-3): 141-157.

Mitchell, C. A. (1994). “Bioregenerative life-support systems.” American Journal of Clinical Nutrition **60**(supplement): 820S-824S.

Molina, G. E., F. F. G. Acien, et al. (1999). “Photobioreactors: Light regime, mass transfer, and scaleup." Journal of Biotechnology **70**(1-3): 231-247.

Mori, K. and e. al (1989). "Design for a Bioreactor with sunlight supply and operations systems for use in the space environment." Advances in Space Research **9**(8): 161-168.

Mori, K., H. Ohya, et al. (1987). "Sunlight Supply and Gas Exchange in MicroAlgal Bioreactor." Advances in Space Research **7**(4): 47-52.

Nakhost, Z., M. Karel, et al. (1987). "Non-Conventional Approaches to Food Processing in CELSS. I-Algal Proteins; Characterization and Process Optimization." Advances in Space Research **7**(4): 29-38.

Nandeesha, M. C., B. Gangadhar, et al. (1998). "Effect of feeding Spirulina platensis on the growth, proximate composition and organoleptic quality of common carp, Cyprinus carpio L." Aquaculture Research **29**(5): 305-312.

Oguchi, M. and e. al (1989). "Closed and Continuous Algae Cultivation System for Food Production and Gas Exchange in CELSS." Advances in Space Research **9**(8): 169-177.

Oguchi, M., K. Otsubo, et al. (1987). "Food Production and Gas Exchange System Using Blue-Green Alga (Spirulina) for CELSS." Advances in Space Research **7**(4): 7-10.

Oguchi, M., K. Otsubo, et al. (1989). "Closed and Continuous Algae Cultivation System for Food Production and Gas Exchange." Advances in Space Research **9**(8): 169-177.

Olguin, E. J., B. Hernandez, et al. (1994). "Simultaneous high-biomass protein production and nutrient removal using Spirulina maxima in sea water supplemented with anaerobic effluents." Journal Article: 576-578.

Olvera-Novoa, M. A., L. J. Dominguez-Cen, et al. (1998). "Effect of the use of the microalga Spirulina maxima as fish meal replacement in diets for tilapia, Oreochromis mossambicus (Peters), fry." Aquaculture Research **29**(10): 709-715.

Ortega-Calvo, J. J., C. Mazuelos, et al. (1993). "Chemical composition of Spirulina and eukaryotic algae food products marketed in Spain." Journal of Applied Phycology **5**(4): 425-435.

Petersen, G. R. (1988). "Reproducible analysis of microbial food for advanced life support systems." Enzyme Microbial Technology **10**: 586-592.

Petersen, G. R., P. K. Seshan, et al. (1989). "Phase Separated Membrane Bioreactor: Results from Model System Studies." Advances in Space Research **9**(8): 185-193.

Petersen, G. R., B. O. Stokes, et al. (1983). “Enhancement of Carbohydrates in a Methylotropic Yeast.” Enzyme Microbial Technology **5**: 337-341.

Qiang, H., Y. Zarmi, et al. (1998). “Combined effects of light intensity, light-path and culture density on output rate of Spirulina platensis (Cyanobacteria).” European Journal of Phycology **33**(2): 165-171.

Qiuhui, H. (1999). “Supercritical carbon dioxide extraction of Spirulina platensis component and removing the stench.” Journal of Agricultural and Food Chemistry **47**(7): 2705-2706.

Radmer, R., J. Cox, et al. (1987). “Biomass Recycle as a Means to Improve the Energy Efficiency of CELSS Algal Culture Systems.” Advances in Space Research **7**(4): 11-15.

Rahman, A. and N. MacLean (1998). “Production of Lines of Growth Enhanced Transgenic Tilipia (Oreochromis niloticus) Expressing a Novel Piscine Growth Hormone Gene.” New Developments in Marine Technology.

Resh, H. M. (1989). Hydroponic Food Production: a Definitive Guidebook of Soilless Food Growing Methods. Santa Barbara, Woodbridge Press Publishing Company.

Richmond, A., Ed. (1986). CRC Handbook of Microalgal Mass Culture. Boca Raton, CRC Press, Inc.

Richmond, A. and N. Zou (1999). “Efficient utilisation of high photon irradiance for mass production of photoautotrophic micro-organisms.” Journal of Applied Phycology **11**(1): 123-127.

Romano, I., M. R. Bellitti, et al. (2000). “Lipid profile: A useful chemotaxonomic marker for classification of a new cyanobacterium in Spirulina genus.” Phytochemistry (Oxford) **54**(3): 289-294.

Rose, A. H. (1981). The Microbiological Production of Food an Drink. Scientific American**:** 95-104.

Salazar, M., E. Martinez, et al. (1998). “Subchronic toxicity study in mice fed Spirulina maxima.” Journal of Ethnopharmacology **62**(3): 235-241.

Sanchez, M. A., G. A. Contreras, et al. (1999). “Comparative evaluation of compact photobioreactors for large-scale monoculture of microalgae.” Journal of Biotechnology **70**(1-3): 249-270.

Scheldeman, P., D. Baurain, et al. (1999). “Arthrospira ('Spirulina') strains from four continents are resolved into only two clusters, based on amplified ribosomal DNA restriction analysis of the internally transcribed spacer." FEMS Microbiology Letters **172**(2): 213-222.

Seddon, M. R., M. J. Fettman, et al. (1994). "Practical and clinical concerns during spaceflight." American Journal of Clinical Nutrition **60**(supplement): 825S-830S.

Sheleff, G. and C. J. Soeder, Eds. (1980). Algae Biomass: Production and Use. Amsterdam, Elsevier/North-Holland Biomedical Press.

Shils, M. E., J. A. Olson, et al., Eds. (1994). Modern nutrition in health and disease. Malverne, Lea & Febiger.

Shimada, H., K. Kondo, et al. (1998). "Increased Carotenoid Production by the Food yeast Candida utilis through Metabolic Engineering of the Isoprenoid Pathway." Applied and Environmental Microbiology **64**(7): 2676.

Singh, G., V. S. Chauhan, et al. (1999). "Effect of continuous and cyclic illumination on the growth of different Spirulina isolates." Microbios **99**(393): 83-88.

Torzillo, G., P. Bernardini, et al. (1998). "On-line monitoring of chlorophyll fluorescence to assess the extent of photoinhibition of photosynthesis induced by high oxygen concentration and low temperature and its effect of the productivity of outdoor cultures of Spirulina platensis (Cyanobacteria)." Journal of Phycology **34**(3): 504-510.

Tredici, M. R. and G. C. Zittelli (1998). "Efficiency of sunlight utilization: Tubular versus flat photobioreactors." Biotechnology and Bioengineering **57**(2): 187-197.

Vachhani, A. K. and A. Vonshak (1996). "Recombination protein A gene, recA, from Spirulina platensis IAM-M135." Journal of Applied Phycology **8**(6): 563-564.

Vonshak, A., Ed. (1998). Spirulina platensis (Arthropira): Physiology, Cell-biology and Biotechnology. London, Taylor & Francis Ltd.

Vonshak, A. (1998). "Mass culturing of microalgae; from open ponds to closed systems." Journal of Phycology **34**(3 SUPPL.): 61-62.

Wood, B. J. B., P. H. K. Grimson, et al. (1999). "Photoheterotrophy in the production of phytoplankton organisms." Journal of Biotechnology **70**(1-3): 175-183.

Yamaguchi, K. (1996). "Recent advances in microalgal bioscience in Japan, with special reference to utilization of biomass and metabolites: A review." Journal of Applied Phycology **8**(6): 487-502.

Zaborsky, O. R. (1999). “Marine bioprocess engineering: The missing link to commercialization.” Journal of Biotechnology **70**(1-3): 403-408.

Zeng, M.-T. and A. Vonshak (1998). “Adaptation of Spirulina platensis to salinity-stress.” Comparative Biochemistry and Physiology A **120**(1): 113-118.

4.8 Habitat Production

Figure 4.8.1 shows the overall flowsheet for habitat production by the robotic ALPH factories that land at the colony site as described in Section 4.2, the first step is the deployment of the warm water melt lines with their collapsed warm water balloons.

The next step is to pump warm water from the ALPH reactor into the collapsed balloons, causing them to expand against, and melt away, the surrounding ice, as illustrated in Figure 4.2.7. The melt rate is relatively fast, producing 10 meter diameters cylindrical habitats in less than a month (Figure 4.2.6). As the cavity diameter increases, the balloon continues to expand and press against the surrounding solid ice, insuring good heat transfer.

After the cavity has reached its full diameter, the warm melt water is pumped out and the cavity pressurized with breathable air (79% N_2, 21% O_2).

The cavity is then put into a standby state and kept at the temperature of the ice sheet (-100/ C) until the first group of colonists land at the site (Figure 4.8.1). The period between the creation of the habitat cavity and the astronauts landing will be at least 12 months, and possibly longer, depending on project scheduling.

After landing, the astronauts will switch on the warm water heat system for the habitat cavities, quickly bringing their internal temperatures to ~30/ C. The heat loss from the habitat interior into the surrounding ice sheet is kept small by air insulating plastic/air cell structure illustrated in Figure 4.2.8. The astronauts would then move into the habitats.

The habitats will be spacious and comfortable. Assuming a total of 5 habitats, each 10 meters in diameter, and an initial landing party of 10 astronauts, the corresponding floor area is 40 m^2 per person (400 ft^2 per person).

After arrival of the astronauts, the habitats would be furnished with standard type furnishings - beds, chairs, desks, etc. - most of these furnishings would be built by the astronauts, using both the stockpiled and now materials produced at the colony site. Only a small fraction of the furnishing would be brought from Earth.

As the colony size increases, more habitats would be created; moreover, the floor area per person would increase, ultimately to ~3000 ft^2 per person for both living and work quarters.

4.9 Supply Stockpile Available to Initial Colonists

Figure 4.9.1 illustrates the time line for ALPH operation, at the Xanadu outpost. The first step is the touchdown of the ALPH units at the landing site (Phase 0). For Xanadu, two independent co-located ALPH units appear desirable. This provides redundancy and reliability, without imposing a significant weight burden. Using even more ALPH units is feasible, but the additional redundancy does not appear necessary. After touchdown, the two ALPH units independently deploy (Phase 1). The reactors move downwards into the ice sheet, while the multiple storage and habitat cavities are created. Each independent ALPH unit would create two separate storage cavities for each material produced (i.e., two separate cavities for liquid H_2, two separate cavities for liquid O_2, etc.). The two ALPH units would then have created four separate storage cavities for each material. The cavities and production rates are sized so that a single filled cavity, out of the set of four, would be sufficient to support the crew and their exploration activities during the stay on Mars, and to return them to Earth at the completion of the mission. This arrangement provides flexibility and reliability. Only one of the two ALPH units has to operate (the other can fail completely) and only one of the two separate storage cavities created by the functioning ALPH has to be filled, so that the operating ALPH unit need only deliver 50% of its design capability to meet mission requirements. Since ALPH already would have successfully demonstrated a high degree of reliability through validation tests on Earth ice sheets, its overall reliability level for a Mars mission would be extremely high.

Actual production of the materials stockpile would begin in Phase 2. As illustrated in Figure 4.9.1, most of the 21 month interval between the landing of the ALPH units on the Polar Cap and the department of the crew from Earth, would be devoted to stockpiling fuel, propellants, plastic construction materials, and food. The crew would not leave Earth unless at least two of the independent storage cavities for each material were fully stocked, providing a large margin for the mission. This mission would further increase as the manned portion of the mission proceeded, since two new and additional ALPH units would land at the Xanadu outpost, generating still more materials along with those generated by the continued functioning of the old ALPH units. By the time of the second manned mission, the outpost would have stockpiled almost ten times as much material as required for the actual mission.

Table 4.9.1 lists cavities created in the ice sheet by the two ALPHs, while Table 4.9.2, summarizes the materials stockpile at the Xanadu outpost held in the four separate storage cavities. The total amount of liquid hydrogen stored is 160 metric tons, while the total amount of liquid oxygen stored is 1680 metric tons. The ratio of the liquid oxygen mass to the liquid hydrogen mass is 10.5/1, which is substantially higher than the 8/1 ratio characteristic of water electrolysis. This is a result of the use of a substantial fraction of the electrolysis hydrogen to generate liquid methane, methanol, and plastic. The excess oxygen is liquefied to be used as an oxidant for burning the methane, and methanol, fuel propellants, and for the outpost's air supply. Figure 4.3.4 shows the power distribution load for one ALPH generation unit. Most of the total 535 kW(e) output power is used for water electrolysis [360 kW(e)] and H_2 electrolysis [53 kW(e)]. Small amounts are used for liquefaction of oxygen and methane and pressurization of atmospheric CO_2 for the process units. Of the 100 kW(e) balance, 30 kW(e) is used for food production (i.e., powering the lights used for photosynthesis) and the rest [70 kW(e)] for miscellaneous loads and contingency. The mass budget for an ALPH unit is summarized in Table 4.9.3. The material production amounts and power loads shown are illustrative and can be readily adjusted, depending on the results of more detailed mission studies.

5 DESCRIPTION AND PERFORMANCE OF A EARTH-MARS-EARTH TRANSPORT ARCHITECTURE

5.1 Transport Architecture

Figure 5.1.1 and 5.1.2 illustrates the proposed baseline architecture for the transport of colonists to and from Mars. Two fueling depots are assumed, the first in high Earth orbit - nominally GEO, though other high orbit locations could be used - and the second in Mars orbit. The depots utilize spent external tanks from space shuttle flights. The extra ΔV needed for a shuttle tank to achieve LEO is small, on the order of 100 meters per second. After achieving LEO, the tanks would be boosted to GEO or transported to Mars orbit.

Starting from Earth, a habitat vehicle with an attached OTV vehicle is launched by a Saturn V class booster into LEO (Stage 1 in Figure 5.1.1). The habitat vehicle mass is 93 metric tons, and is sized for a maximum crew capacity of 22 persons. After reaching LEO, the habitat is raised to GEO using its attached OTV, which is powered by 3 MITEE engines. At GEO, the habitat vehicle is mated with a cycler vehicle (Stage 2) which travels back and forth between GEO and Mars orbit. The cycler vehicle is refueled from the GEO depot, using H_2 propellant which has been transported there from Mars orbit by a cargo propellant vessel. The cycler vehicles then propels the habitat towards Mars, with a 105 day trip time (Stage 3).

Upon reaching Mars, the habitat and cycler separate. The habitat aerobrakes and makes a 2 km/sec controlled burn for land at the colony site (Stage 4), while the cycler does a 4 km/sec burn for orbit capture (Stage 5) and rendezvous with the Martian fueling depot (Stage 6). The cycler remains at the depot until a returning habitat lifts off (Stage 7 in Figure 5.1.2) from the colony site and reaches the depot. (The habitat only uses H_2/O_2 engines, not nuclear engines, so there are no safety or environmental concerns). There it mates with the cycler (Stage 8) which is refueled with H_2 propellant lifted up from Mars. The cycler then propels the habitat towards Earth, with a 120 day trip time (Stage 9). Upon reaching Earth, the habitat separates, to aerobrake and land on Earth (Stage 10) while the cycler undergoes a 3.7 km/sec burn (Stage 11) for GEO insertion. (The habitat also does a 2 km/sec burn to decrease the re-entry velocity to 11 km/sec [Apollo type re-entry] for landing.)

Figure 5.1.3 illustrates the propellant transport position of the Earth-Mars-Earth architecture. A fueling shuttle vehicle is used to transport liquid H_2 from the Mars colony up to the fueling depot at Mars orbit (Stages 1 and 2). A portion of this liquid H_2 is used to fuel the cycler for its return with the attached habitat to Earth. The remainder is loaded (Stage 3) into the NTCPV (Nuclear Thermal Cargo Propellant Vehicle) which transports liquid H_2 back to the GEO fuel depot (Stages 4, 5, and 6). The NTCPV then returns to the Mars depot, using its remaining liquid H_2 for the trip (Stage 7).

Table 5.1.1 summarizes the propellant flow requirements for a steady state architecture serving a mature Mars colony of 500 persons. The colonists turnover rate is assumed to be 20% every 2 years, i.e., 100 persons go to Mars, requiring 5 habitat trips, and 100 persons return, also requiring 5 habitat trips. The propellant fuel requirements include: 1) the liquid H_2 transported back to the GEO depot to fuel the cycler/habitat vehicles for their outbound trips to Mars; 2) the liquid H_2 consumed by the NTCPV vehicles in their round trips between Earth and Mars depots to deliver the liquid H_2 cargo to GEO; 3) the liquid H_2 in Mars depot to fuel the cycler/habitat vehicles for the return trip to Earth; 4) the H_2 used by the H_2/O_2 engines in the habitat vehicles as they lift off from the colony site into Mars orbit; and 5) the H_2 used by the H_2/O_2 engines on the fueling shuttles to deliver liquid H_2 payloads to the Mars depot.

The total liquid H_2 production rate of 835 tons per year would require 20 megawatts (thermal) of reactor capacity at the Mars colony site, assuming a power conversion efficiency of 20%, thermal to electric and an operating factor of 90%. This amount of reactor capacity is easily provided. The oxygen production requires no additional power, since it automatically comes along with the H_2 production.

Other Earth-Mars-Earth architectures are possible and may offer even more attractive performance. An alternate architecture based on having the Earth fueling depot located in LEO was investigated. Figures 5.1.4, 5.1.5 and 5.1.6 summarizes the results of this study. This option was not as attractive as the GEO option, however, because of the greater)V requirements for transport to and from Mars, and the requirement to not operate nuclear engines for orbit insertion at low orbital altitudes. The GEO depot location eliminates this requirement.

Details of the various stages involved in the Earth-Mars-Earth transport architecture, including the)V's and travel time for the GEO and LEO architectures, are given in Tables 5.1.2, 5.1.3, 5.1.4, and 5.1.5.

The transport requirements for buildup to a steady state architecture have been investigated, assuming a landing of the first colonists in 2018 and a buildup to 500 persons by 2034, as illustrated in 2.3. Figure 5.1.7 shows the numbers of colonists going to Mars and returning to Earth per year (converted to an equivalent annualized basis) as a function of year, together with the number of colonists on Mars, also as a function of year.

The buildup rate could be faster or slower, depending on the number of habitats launched every 2 years, and the fraction of the colony that chooses to return to Earth. The 20% return rate at steady state is equivalent to an average stay of 10 years of Mars. Some colonists probably will stay there permanently, while others will want to leave after 2 years. It is not possible to predict what the actual return rate will be, but 20% does not appear unreasonable.

Figure 5.1.8 shows the launch mass to Earth orbit per colonist traveling to Mars as a function of launch year. The value depends slightly on launch year, with an average of 8.6 tons/ colonist trip. This is a factor of approximately 10 smaller than the launch mass needed for astronauts exploring Mars using the individual mission approach, in which most of the supplies and propellants for the mission would have to be launched from Earth.

Figure 5.1.9 shows the cumulative total integrated mass amount of H_2 propellant transported from Mars to the Earth GEO depot as a function of launch year, together with the cumulative buildup of H_2 propellant in the depot as a function of year. The H_2 transport rate from Mars to GEO is considerably greater than the amount required by the Earth to Mars trips (otherwise, the cumulative H_2 buildup would equal zero at all times). A portion of this excess transport can be considered as a reserve for future trips, while the rest can be used for other purposes, including propellant for the maintenance of solar power satellite attitude and travel to and from a manned lunar base.

5.2 The MITEE Propulsion System

Nuclear propulsion is a key technology element for establishing a Mars colony. It greatly reduces the mass of propellant that must be launched into orbit, and shortens the trip time to and from Mars.

Figure 5.2.1 illustrates the design features of the MITEE (MInature ReacTor EnginE) nuclear engine (1,2). The reactor core consists of a close packed array of 37 separate beryllium metal pressure tubes, each of which contains an inner annular fuel zone which is enclosed by a surrounding outer lithium hydride moderator zone. Cold hydrogen propellant enters at the top end of each pressure tube, and flows longitudinally down through an outer plenum that is located between the pressure tube and moderator region.

As the hydrogen flows down through the plenum, some of it peels off the main longitudinal flow and flows radially inwards towards the axis of the pressure tube. This radial flow first passes through the outer moderator zone, and then through the inner fuel zone. The local radial flow rate of the hydrogen propellant is controlled by the local effective porosity of the fuel zone, which is fabricated so that hydrogen exit temperature (~3000 K) out of the fuel region into the central hot gas flow channel is the same at all points inside the reactor. This power to flow matching capability, which allows the mixed mean temperature of the hot exit propellant to reach its maximum possible value, results in the highest specific impulse that can be achieved.

The MITEE-type fuel element enables extremely high power densities in the reactor fuel element, and consequently, very compact and lightweight nuclear propulsion engines. Similar type fuel elements were tested in the SNTP-PBR nuclear propulsion program, and demonstrated the capability to operate at a power density of 30 megawatts per liter of fuel region.

The MITEE engine improves on the PRR engine in two important aspects. First, it uses an array of separate individual pressure tubes for the reactor, instead of an array of fuel elements inside a common pressure vessel. This simplifies the construction of the reactor, as well as its development and testing. The development program would concentrate on validating the performance of a single fuel/moderator tube, which would then be replicated to form the complete reactor assembly. In contrast, reactors with an integrated core/vessel must test the complete assembly, and require much longer development time and cost.

Second, the nuclear fuel region inside the MITEE pressure tubes consists of a multi-layer roll of perforated sheets (Figure 5.2.2) of tungsten - UO_2 metal matrix composite, in place of the packed bed of small fuel particles that was used in the PBR engine. The tungsten - UO_2 composite fuel, which was developed in the 1960's, exhibits excellent stability and resistance to high temperature hydrogen corrosion, being able to operate for many hours in 3000 K hydrogen. Moreover, the radial flow of the hydrogen coolant through the perforated fuel sheets can be controlled more precisely than through a random packing of fuel particles, enabling a higher average outlet hydrogen temperature.

The MITEE core has 37 elements, each being a pressure tube, arranged in a hexagonal pattern. The core is surrounded by one or two rows (depending on design) of reflector elements, which have the same pitch as the fuel elements, and contain the same moderating material as the core. The moderator in the MITEE engine is lithium-7 hydride held inside the beryllium tubes. Hydrogen cools the moderator in the reflector before flowing into the core.

The fuel element has three zones: 1) An outer zone of a beryllium metal matrix composite, containing graphite fibers that are infiltrated with uranium carbide or oxide, 2) A middle zone of molybdenum metal matrix composite, containing uranium oxide (UO_2) particles, and 3) An inner zone of tungsten metal matrix (the tungsten will be enriched in ^{184}W to reduce parasitic neutron losses) composite containing uranium oxide (UO_2) particles.

The heat transfer area in the perforated metal matrix (Figure 5.2.2) is controlled by the hole diameter and number of holes. Studies indicate that a perforation fraction of ~ 25% results in acceptable heat transfer performance. The gas flow holes through the sheets are located in a grid pattern of slightly depressed channels formed in the sheets. When the sheets are layered together, the raised portions prevent closure of the holes in the sheets. Gas exiting through the holes in one sheet then flows to, and enters, the holes in the next sheet. This flow arrangement mixes the gas flow between sheets, and reduces the chance of thermal instabilities. The first sheet in the multi-layer stack has smaller holes in order to distribute and match the hydrogen flow to local variations in the radial, axial, and azimuthal nuclear power production. In effect, it functions like the cold frit in the PBR.

If the total temperature of the rocket exhaust is 3000 K the fuel temperature (most probably where the flow exits the core)is somewhat higher than 3000 K. The temperature difference between the solid fuel and its adjacent coolant is the "film drop," which varies locally. For maximum performance, the coolant should exit the nozzle at the highest possible temperature. At the same time, the solid fuel must be kept below its melting temperature. Given these constraints, the hydrodynamic design aims to minimize the film drop.

The film drop is calculated from a heat transfer analysis of the fuel elements. The MITEE fuel element is formed by rolling a perforated sheet into an annular shape (Figure 5.2.1), which is held between two porous frits. Because the lateral heat conduction in the sheet is large, i.e., the lateral temperature gradients in the "raised portions" of the sheet are negligible. Due to the complex nature of this flow passages through the fuel region, a detailed convective heat transfer analysis was not carried out at this stage of design. Instead, a conservative approach was adopted in which all of the convective heat transfer was assumed to take place on the cylindrical inner surfaces of the perforating holes. This assumption is reasonable because the flow velocity is highest inside the tubes and a new (and thin) boundary layer forms at the entrance of each of the tubes. Because of the high conductivity of the metallic fuel matrix, the wall temperature of the tube is essentially constant. The heat transfer problem is thus one of internal flow in short tubes with the tube wall at a constant temperature. A heat transfer correlation corresponding to these conditions is presented in Rohsenow, et al, (3). Table 7 in Chapter 7 of Rohsenow presents a correlation between the average Nusselt number in the tube and a nondimensional length of the tube x^+, for a range of Prandtl numbers. The nondimensional tube length is defined as $x^+ = (x/r)/(RePr)$. The geometry of the fuel sheet used for the analysis is illustrated in Figure 5. For this geometry the voidage is 37% and the open (flow) area is 23%.

The reactor design was analyzed using the above model. The fuel thickness (0.886 cm) was assumed to be composed of a wrap of 35 layers. It was further assumed that hydrogen enters the fuel region at 100 K (note: hydrogen is heated from 30 K to 100 K in the moderator) and exits at 3000 K. Based on these boundary conditions, the calculated temperature variation in the fuel region of the core is shown in Figure 5.2.3. The most significant result is that the film drop at the exit of the core is about 40 deg C. Thus, for an effective chamber temperature of the propellant of 3000 K, the fuel element will experience a maximum temperature of 3040 K. This appears achievable.

Since the film drop has a small, but significant, effect on the performance of the rocket, a simple parametric analysis aimed at possibly reducing the film drop was conducted. It is apparent that the film drop varies inversely with the effectiveness of heat transfer process from the fuel to the coolant. The heat transfer process can be enhanced either by increasing the heat transfer coefficient or by increasing the heat transfer area per unit core volume. The latter effect can be achieved simply by scaling down the geometry of the flow passages. In other words, if we had geometrically similar sheets of fuel, but decreased their thickness, the heat transfer area per unit volume would be increased. In the example described previously the fuel was composed of 35 layers. The problem was re-analyzed, keeping the overall dimensions of the fuel region constant, but altering the thickness of the fuel sheets. Clearly, for minimizing the film drop, it is desirable to decrease fuel sheet thickness. The minimum thickness of the fuel sheet will probably be limited by mechanical considerations, rather than thermal hydraulics.

Since the heat transfer model is conservative, it appears likely that the actual film drops will be smaller than projected. Moreover, since the temperature of the fuel is so close to that of the hydrogen propellant at the hot side of the fuel element, it is very likely that a propellant outlet temperature in the range of 2750 to 3000 K (I_{SP} ~900 to 1000 seconds) can be achieved using the tungsten matrix fuel in the final third of the MITEE fuel element.

The design of a nuclear reactor powered rocket involves a variety of analyses, including reactor physics, heat transfer, fluid dynamics, and stress. Reactor size is first estimated based on input from systems analyses and mission requirements. This estimate is first checked for criticality. Cores that cannot go critical are not feasible and eliminated. Acceptable designs are then optimized by iterating among the reactor physics, heat transfer fluid dynamics and stress analyses. The resultant design is then integrated into an overall engine system and startup transients analyzed.

The dimensions of the reactors considered here are based on a fuel element average power density of 10 MW/L and a total reactor power of 75 MW. The fissile material in the fuel element is ^{235}U (enriched to 93%). In all cases the diameter of the core equals its height. The core consists of 37 hexagonal elements, reflected by either one or two rows of reflector elements of equal size. The only variable to change the multiplication factor (k_{eff}) of the core is the element pitch/diameter ratio. Increasing the pitch/diameter ratio increases the amount of moderator in the core, thus softening the neutron energy spectrum. If the core is under moderated, increasing the pitch/diameter ratio increases the value of k_{eff} (and vice-versa). If the core is over moderated, increasing the pitch/diameter ratio will reduce the value of k_{eff} and vice-versa. This effect is illustrated in Figure 5.2.3. The fuel consists of tungsten, molybdenum, and beryllium cermet sheets, each containing a volume fraction of 50% UO_2. The sheets are layered together to form the annular fuel element. The beryllium also acts as a moderator within the fuel element. The core moderator and the reflector moderator consist of a lithium/beryllium composite. Two rows of reflector elements are included, resulting in a total of sixty one elements in the reactor. All analyses were carried out using the Monte Carlo code MCNP (4). This code uses combinatorial geometry to represent the reactor, with a point-wise cross section representation. The MCNP analyses make no simplifying assumptions with regards to reactor geometry and nuclear data. Results from the critical experiments carried out on PBR reactor assemblies agreed very closely with predictions from the MCNP code.

The predicted reactor mass is also shown on Figure 5.2.3. The mass increases with increasing pitch/diameter ratio, causing the thrust/weight ratio to decrease. If values of k_{eff} greater than 1.05 are acceptable, the highest thrust/weight ratio is achieved for a reactor with a core pitch/diameter ratio of 2. This design is somewhat under moderated, and the addition of hydrogen propellant during startup would increase the multiplication factor. The most stable reactor at startup would have a pitch/diameter ratio of 2.5, resulting in the reactivity being unaffected by the addition of the hydrogen propellant. The issue of MITEE reactor stability during startup, and how it impacts the choice of pitch/diameter ratio, requires further detailed analysis of the transient effects during startup. However, based on transient start up analyses of the PBR, it appears possible to safely start a MITEE reactor even if it is initially under-moderated.

The dimensions for the series of ^{233}U and ^{235}U fueled reactor cores studied are shown in Table 5.2.2. In all cases the fuel consisted of 93% enriched uranium. Lithium-7 hydride/beryllium is assumed for the moderator and reflector with a power density of 10 MW/L is assumed in the fuel region. The core consists of 37 fuel elements and is reflected by 24 reflector elements.

Multiplication factors and mass estimates for the core (fuel and moderator) and total reactor mass corresponding to the above cases are given in Table 5.2.2.

The results show the clear advantage of using ^{233}U fueled reactors. Since ^{233}U has superior nuclear properties to ^{235}U, it enables smaller, lighter reactors. By operating the ^{233}U reactors at modestly increased power densities, the same power and thrust as the heavier ^{235}U fueled cores can be obtained, significantly increasing the thrust/weight ratio. Finally, the amount of UO_2 required is seen to be lower in the case of the ^{233}U fueled cores. The availability and handling requirements for ^{233}U fuel in nuclear rocket applications would have to be evaluated in more detail, but it has been used in civilian power reactors, so, it should be practical.

Table 5.2.1 summarizes the principal parameters of the MITEE engine. The small size and weight of MITEE allows it to perform a wide range of exploration missions, both unmanned and manned (1,2). Employed as a single engine that would operate in deep space after a safe orbit had been established, MITEE can propel faster, direct trajectory unmanned exploration missions to the outer planets - e.g., 2 years to Jupiter, 3 years to Saturn, 5 years to Pluto - as well as missions not possible with chemical engines - e.g., Europa sample return, Pluto orbiter, etc. The IMLEO launch vehicles used for these MITEE missions will be considerably smaller than if upper stage chemical engines were used.

Figure 5.2.5 illustrates the much larger)V capability of MITEE engines, as compared to the best H_2/O_2 chemical engines. MITEE can deliver)V's up to ~22 km/sec, vs only about 10 km/sec for H_2/O_2 engines. Applied to unmanned high)V exploration missions, MITEE enables mission performance not achievable by chemical engines, as well as new types of missions that are not even feasible with chemical engines. Applied to the Earth-Mars-

Earth architecture described in the following section, MITEE enables a transport capability between the two planets that would be impossible with chemical engines. Put simply, large scale exploration and colonization of Mars can only be done using nuclear propulsion and power.

In addition to greatly reducing the IMLEO requirements for Earth-Mars transport, MITEE engines have major operational advantages over other nuclear thermal propulsion engines, such as NERVA. MITEE enables a robust multiple engine on the manned space vehicles traveling between Earth and Mars. If one or two of the MITEE engines were to fail, the mission could still be carried out successfully. In contrast, if space vehicles were equipped with much larger, high thrust type NERVA engines, failure of even one engine could prove catastrophic. Moreover, after firing, the small MITEE engine could be detached from the space vehicle eliminating the need to shield from the residual radioactivity. In a trip from GEO orbit to Mars orbit, for example, those MITEE engines used for the TMI (Trans Mars Injection) burn would be detached from the space vehicle and sent onto a non-returning trajectory. Upon reaching Mars orbit, those engines used for orbit insertion would also be discarded after use. New engines would then be attached at the fueling depot.

Used in this manner, nuclear propulsion reactors do not pose any safety or environmental problems. The residual radioactivity is extremely small - the firing of a MITEE engine would generate only 10^{-6} of the long lived residual radioactivity present in a typical Earth based power reactor, and 10^{-8} of the radioactivity already present in Earth's biosphere. Moreover, the spent MITEE engines would travel in deep space on non-returning trajectories, and would never impact Earth or Mars.

5.3 Vehicle Designs for Earth-Mars-Earth-Transport

Figures 5.3.1 through 5.3.5 illustrates the principal features of the habitat, OTV, cycler, fueling shuttle, and NTCPV vehicles used in the Earth-Mars-Earth architecture. All of these are new vehicles and would require substantial development programs. However, the OTV, cycler, and NTCPV vehicles are relatively simple in construction, being essentially propellant tanks with attached engines that operate only in space, and that do not have to land or take off from planetary surfaces.

The number of vehicles required in the fleet will start small, and increase with time as the colony grows.

<u>References:</u>

1. Powell, J., et al., "An Ultra Lightweight Nuclear Engine for New and Unique Planetary and Science Mission," Paper IAF-98-R.1.01, 49th International Astronautical Congress, Melbourne, Australia, Sept. 28 - Oct. 2, 1998.

2. Powell, J., et al., “The MITEE Family of Compact Lightweight Nuclear Thermal Propulsion Engines for Planetary Space Exploration,” Paper IAF-99-5.603, 50th International Astronautical Congress, Amsterdam, Netherlands, October 4-8, 1999.

6 XANADU: A REFERENCE DESIGN FOR A LARGE MARS COLONY ON THE NORTH POLAR CAP

6.1 Quality of Life in Xanadu

Figure 6.1.1 illustrates the four main functions and features of life in a mature Martian colony. All are vitally important to the health and success of the colony. Virtually all of the life support requirements can be met using the materials produced by ALPH. As shown in Figure 6.1.2 and 6.1.3, the colonists will be able to live very comfortably, with as good a diet as they would have on Earth, ample Earth type air (1 atm, 20% O_2) and water, and living quarters at least as spacious as those for the average American. Moreover, ALPH will provide ample power and space heat, so that the living and work quarters will be well lit and comfortably heated. The one area where there would be constraints is the ability to experience and enjoy large surface parks in the open sunlight. Substantial size parks, gardens and lakes could be created under the surface of the ice cap (Coleridge's "caverns measureless to man, down to a sunless sea"), but they would have to artificially, not naturally, lit. Visits to a transparent domed enclosed area on the surface would be possible, but not unencumbered walks outside. Any outside visit would essentially require a spacesuit.

Because of the capability and versatility of ALPH to produce very ample supplies of air, water, food, materials, and living space, the Mars colonists will not be subject to physical stress and difficult, risky living conditions. In fact, living conditions in the Mars Colony will be very comfortable and not a concern.

Of more concern will be the psychological stress experienced by colonists - that is, their virtually complete isolation from Earth, the long time, lags, - up to a half an hour - for conversations with Earth, the absence of an open Earth type environment, and the claustrophobic feeling that it would take months to get back to Earth if one wanted to.

Entertainments and diversions can help alleviate these problems, as can literature, videos, and personal communications sent from Earth. Also, the interest and excitement generated by scientific discoveries on Mars will help to alloy psychological stress. However, the best help and support will probably come from fellow colonists. This is another strong argument for having a large colony size of several hundreds of people, rather than a base of few people.

6.2 Exploration Capabilities

Exploration of Mars would be the driving force behind the colony, and the reason why a colonist would choose to live there - much like the reason that people choose to go to

Antarctica. Accordingly, the colony would be very strongly oriented to discovering as much as they could about Mars, and would seek to maximize exploration capabilities. Figure 6.2.1 shows 3 main modes for exploring Mars. First, the North Polar region could be extensively explored using manned land rovers over distances of a 1000 kilometers or more out from the colony site. The rovers would not be particularly complicated, and could be fabricated from the plastics and metals produced at the colony, and fueled by methane/oxygen supplies from ALPH. Figure 6.2.2 outlines the features and requirements of these manned ice cap rovers. Traveling over frozen ice and permafrost surfaces, they should be able to move at a maximum speed of at least 50 km/hour (30 mph). A 2 week trip in a pressurized cabin with periodic excursions in space suits onto the surface appears to be a practical exploration regime. A 2000 km round trip would require 70 hours of driving time, or about 5 hours daily, which is reasonable.

The crew would take measurements of local conditions at promising locations, collect samples for return to the colony, and emplace instruments for continuously monitoring and recording data on pressure and temperature, wind speed, dust content, seismic activity, etc. They could also emplace MICE units to travel inside the ice cap to investigate its internal structure, composition, etc.

The second mode of exploration would use unmanned flyers to explore these regions that were beyond the maximum range of the land rovers. As illustrated in Figure 6.2.1, the flyers could touch down at a number of locations, nominally on the order of 1000 kilometers apart, to take measurements and visual records, and to collect samples for return to the colony. The flyers, which would be powered by a compact, ultra lightweight nuclear reactor, and use atmospheric CO_2 for propellant, would have virtually unlimited range. The flyers would be able to visit any location on Mars, even as far away as the South Pole.

Figure 6.2.3 lists the principal features of the unmanned flyer. Using stored outboard liquid CO_2 propellant, it would be able to land and take off vertically at slow speed, i.e., like a VTOL, Harrier type jet. After takeoff, it would accelerate to supersonic M = 2 flight (470 meters/sec on Mars), using CO_2 from the Martian atmosphere as the propellant. The CO_2 would be directly absorbed in a molecular sieve type of material (e.g., activated carbon or zeolite) and periodically desorbed using hot gas from the reactor heat source. This temperature swing absorption (TSA) cycle would effectively compress the ram intake CO_2 up to the ~10 atmospheres pressure level, where it would then pass through the reactor to be heated to an outlet temperature of ~2000 K.

The reactor thermal power for the flyer is approximately 1 megawatt, a modest level readily delivered by a compact gas cooled unit. The diameter of the ram inlet that collects the CO_2 propellant is only 25 centimeters. The unmanned flyer would not land and take off from the colony site but rather at a site several kilometers distant, to allow the retrieval of samples and maintenance efforts to be carried out remotely. The residual radioactivity on the reactor would not pose any danger or problems for the colony. The stored liquid CO_2

inventory on the flyer would be replenished at each touchdown point, using an on-board compressor and liquefier to capture atmosphere CO_2. The replenishment process, which would take a few hours, enables the flyer to vertically take off and land at its next destination.

The third exploration mode, as illustrated in Figure 6.2.1 is by manned flyers. Use of a nuclear propulsion engine for manned flight poses risks, and is not necessary. Instead, the manned flyers would carry liquid methane/oxygen fuel to heat atmospheric CO_2 for propulsion. Given the low density of the Martian atmosphere and the consequent inefficiencies of flight in it, it does not appear possible to fly for long distances with a single load of methane/oxygen fuel. Rather, periodic depots of methane/oxygen fuel would be established using the unlimited range unmanned flyers. The manned flyers would then fly from depot to depot refueling with methane/oxygen at each stop. The depots would be laid out so that each represented a promising site for scientific exploration, allowing both the refueling and exploration process to be carried out at the same time. The nominal distance between depots would be about 1000 kilometers. With sufficient depots, manned flyers could travel all the way to the South Pole, if desired.

Figure 6.2.4 outlines an overall exploration program for the Xanadu colony based on the three above exploration modes. This program, which appears will be within the capabilities of a 500 person colony that would not be restricted as to the amount of propellants and supplies available for exploration, would yield an enormous volume of new and exciting knowledge about Martian climatology, geology, meteorology, hydrology, seismology, and hopefully, even paleontology.

Such an exploration program should provide a definitive answer as to whether life ever existed on Mars, and whether it spontaneously arose there, or was it transported as microbes from Earth. Such life forms might even be revivable, as 200 million plus old Earth forms recently were. It may even be discovered that life originated on Mars and then was transported to Earth by asteroid impact events.

Over a 10 year period, a total of hundreds of sites all over Mars would be investigated in detail, and large amounts of samples returned to the colony site for analysis. A substantial amount of samples would also be returned to Earth. Such an exploration program would provide a hundreds of times greater amount of information than would be obtained from a small number of individual missions.

6.3 Materials Production and Manufacturing Capabilities

A main activity for Xanadu is associated with providing the Earth-Mars-Earth transport architecture. As described previously, this involves refueling habitat vehicles for their trips back to Earth, lifting liquid H_2 payloads to the Mars orbital depot via trips of the fueling shuttle (approximately 15 trips per year are required), and periodic astronaut trips to the depot to service and maintain the depot.

A second main activity for Xanadu is the production of the materials and supplies needed to perform the previously described activities - i.e., life support, exploration of Mars, and maintenance of the Earth-Mars-Earth transport architecture. This production would use ALPH process methods and nuclear reactors. The original ALPH units used to establish the colony totaled 5 MW(th) (1MW[e]). As the colony grows, the power rating of the individual ALPH reactor will also likely increase, probably to ~10 MW(th). Table 6.3.1 summarizes production rates for the principal supplies and material needed for life support, exploration, and Earth-Mars-Earth transport in a 500 person Mars colony. The amount shown are quite generous; however, they could be considerably greater, if desired, without affecting the viability of the colony concept.

Several conclusions can be drawn from this example. First, the total reactor power required is modest, even for a 500 person colony. Six small 10 MW(th) reactors would supply more than enough electric power, space heat and air and water for the colony, plus all the materials and supplies required, plus a rapidly growing stockpile of food, propellants, oxygen, fuels, etc. that by itself could sustain the colony for years. Second, most of the process is required for hydrogen production from water electrolysis, which is an extremely well developed technology. No surprises or problems are anticipated in producing hydrogen, oxygen, water and air for the colony. Third, the electric power generation technology is very well developed and available right now. The steam cycle efficiency of 20% is extremely conservative; Earth based power plants routinely achieve much higher efficiencies.

Fourth, most (80%) of the oxygen produced is discarded, even after a stockpile equal to 50% of the consumption rate is added. The air losses, which have already been over estimated, could be increased 100 fold without requiring additional oxygen generation. Fifth, to support a substantial colony, a very large amount of water, tens of thousands of tons per year, is required, both for life support and for materials production. It is very doubtful that this amount of readily accessible water or sub-surface ice will be available at any location on Mars other than the North Polar Cap. Certainly, the Polar Cap is the logical site for a colony. Sixth, nuclear power is a necessity if humanity is to have a substantial colony on Mars. Solar simply cannot supply the amounts of power and heat required by a colony, given the technical difficulty of construction on Mars, the problems of dust, and the substantially reduced solar flux.

Seventh and finally, any significant colony on Mars must be self supporting with only a small fraction of its needs supplied from Earth. Moreover, in addition to supporting itself, it will have to further minimize the remaining transport requirements from Earth by supplying a large fraction of the propellants and supplies needed for trips to and from Mars.

In the long term, if water is discovered elsewhere, in Mars, either as liquid or as ice, it may be desirable to establish daughter colonies at other sites to better explore the planet. The daughter colonies probably would produce most of their own supplies; however, they also probably would depend on the larger parent colony on the Polar Cap for certain specialized materials and equipment.

Table 6.3.1 basically gives the raw materials from which more complex objects and equipment would be manufactured at the Colony. These would include furniture, lights, clothing, etc. Specialized items, such as computers, analytical equipment, etc., would probably have to be brought from Earth; however, the total mass of such items would probably be small.

Not included in Table 1 are metals and ceramics. Aluminum, iron, and other metals could be extracted from Martian dust and fabricated into wiring, structural beams, etc. Similarly, silicon, silica, alumina, etc. could be extracted from dust and fabricated into high temperature refractories and glasses.

6.4 Colony Buildup and Time Lines

Figure 2.3 shows an illustrative road map for buildup of the Mars Colony based on an initial landing of the first group of colonists in early 2019.

A detailed time line for the number of colonists, the number of spacecraft and spacecraft trips, and the cargo shipments has been developed. Figure 5.1.7, 5.1.8, and 5.1.9 show the results of this analysis. The cumulative number of persons in the Colony, together with the number arriving per year on Mars and the number departing per year, are shown in Figure 5.1.7. A steady buildup of colonists with time is achieved.

By transporting propellant from Mars to Earth orbit, the IMLEO needed per passenger conveyed from Earth to Mars is reduced to less than 10 tons. The Earth based annual IMLEO launch rate during the peak buildup period for the Colony would be approximately 500 metric tons per year. This appears practical.

Figure 5.1.9 shows the cumulative propellant launched from Mars to GEO orbit and the cumulative propellant remaining there after the amount needed for trips to Mars has been used. The surplus propellant is available for other applications, including round trips to the Moon, supplies for lunar bases, and missions to other points in the Solar System.

7 TECHNOLOGY DEVELOPMENT NEEDED FOR XANADU

7.1 MICE Explorers

Development of the MICE system appears primarily as an engineering systems development program rather than one that has to develop new types of materials or micro-miniaturize existing technologies. The MICE reactor and power system uses well established existing materials, and the operating temperatures and power densities are very conservative.

The thermal hydraulics of the melt channel process appears straight forward and the required technology sample. The process can be readily tested in existing ice sheets on Earth, using electrically heated units.

Phase 1 (Figure 3.2.16) involves 3 main tasks: 1) testing electrically heated MICE units in Earth ice sheets, 2) building and testing the MICE reactor and power system, and 3) developing and testing the MICE instrument package. This latter task probably involves the most effort in Phase 1, since it is desirable to maximize the amount and quality of data obtained by a MICE mission.

In Phase 2, all of the MICE system components would be integrated into a single unit, which would be tested in an Earth ice sheet. After validation, the final MICE payload would be ready for launch.

The total development time until launch for the program is estimated at about 7 years. This could probably be reduced to approximately 5 years, depending on the sophistication of the instrumentation that mission planners would require. The amount and degree of instrument development, together with functioning level, probably would be the primary factors determining the length of the development program.

7.2 ALPH Robotic Factory

ALPH would employ the same type of reactor that was developed for the MICE probes. The thermal and electric power rating would be greater, but the basic technology would essentially be the same. The coolant flow rates would be greater, as would diameter of the mini-turbine the steam turbine. The ALPH reactor would be developed and tested on the same time scale, i.e., about 5 years.

There has been very extensive experience with water electrolyzers, and a very well developed industrial base. Development of the ALPH electrolyzers appears to be straight forward and primarily a matter of engineering the design to minimize its mass. Electrical efficiency of the electrolyzer is not a strong driver on design, since additional electrical power can be easily generated by the ALPH reactor. The ice sheet offers an unlimited heat sink, and the mass of the reactor power system is not very sensitive to power output.

Given the extensive experience base on water electrolyzers, it appears likely that an ALPH electrolyzer would be demonstrated in approximately 3 years.

NASA is already working on the development of methanators as part of its planned Mars exploration program. Development of an ALPH methanator would build on this effort.

The technology for conversion of methane to methanol is simple and well developed. Designing a compact process unit to produce ~600 kg per day of methane from methanol appears to be straightforward.

The technology of conversion of CO_2 /H_2 raw materials to polyethylene and similar plastics is also well developed. There is a variety of industrial processes that operate at a wide range of pressures and with different types of catalysts. In general, however, these processes have been optimized for large scale plants. Selection of the best process to use for ALPH will depend, in large part, on their suitability for miniaturization, and what the mass of their ALPH process units would be.

Following selection of the best polymerization process for ALPH, a compact process unit would be designed, built, and tested. This could easily be carried out in 2 to 3 years.

The final ALPH process units are the bioreactors that produce algae and yeast food stuffs for the colonists. Large industrial scale plants have been built for both algae and yeast production, as well as compact, small scale units that would correspond to the production rate, e.g., a few kilograms daily, required for the first group colonists landing on Mars.

The design, construction, and testing of algae and food production units for ALPH appears to be simple and probably could be carried out in 2 to 3 years. The R&D needed to have a Mars ready unit is not so much related to process hardware, but rather on nutritional questions - what percentage of the diet can utilize algae and yeast? Are these long term objectionable elements in the algae, e.g., nucleic acids be minimized or eliminated? Can the algae and yeast cultures be genetically engineered to achieve a more optimum balance of protein, fats, and carbohydrates?

Such R&D will take substantially longer and require more funding than that for just the process hardware. However, it should be possible to develop an optimized mix of algae and yeast, together with texturing and flavoring methods to enhance its dietary appeal, within the next decade.

7.3 MITEE Propulsion Engines

The development of the MITEE engine would utilize the very extensive experience base accumulated by the United States and the Former Soviet Union (FSU). A substantial portion of the development required for MITEE has already been achieved in connection with the PBR (Particle Bed Reactor) program, which was carried out in the US during the late 1980's and early 1990's. In particular, the PBR program. 1) Demonstrated very high power densities in non-nuclear test prototype fuel elements tested in the blowdown mode (~30 MW/Liter, three times the MITEE design value of 10 MW/Liter). 2) Developed very high temperature coated fuel particles and hot frits and demonstrated their ability to operate in 3000 K hydrogen for more than one hour. 3) Tested a “cold critical” PBR nuclear reactor. Detailed measurements of reactor performance were carried out including multiplication factor, three dimensional power distribution, temperature and moderator coefficients, etc., which exhibited excellent agreement with analytical predictions. 4) Fabricated and tested variable porosity cold frits suitable for locally controlling coolant flow to match 3D power distribution in the reactor. 5) Developed a detailed design for a 1000 MW PBR nuclear engine system, including reactor, pressure vessel, nozzle, turbo-pump, and controls. Performance parameters for the PBR engine system included: thrust of 22,000 kilograms, I_{SP} of 1000 seconds, weight of 800 kilograms, and startup time (cold to full power) of 5 seconds. 6) Developed a detailed design for a nuclear engine test facility at the Nevada Test Site and accompanying test plan. Ground testing of full-up PBR engines was planned, prior to operational testing.

The development of the MITEE engine will be significantly simpler, easier, and lower in cost than for the PBR, for the following reasons: 1) The MITEE fuel elements operate at a much lower power density than PBR fuel elements (10 MW/Liter compared to 30 MW/Liter). This greatly eases the thermal hydraulic design, and provides a much greater design margin. 2) The MITEE fuel form (composite metal matrix cermet sheets) is simpler to fabricate and would have greater resistance to hydrogen attack. It is mechanically more stable and easier to control the local fuel density. Unlike the packed bed of fuel particles in the PBR, there is no possibility of fuel settling which might affect local power density, or mechanically deform the confining frits. 3) The coolant flow path through the annular fuel zone in the fuel element is much more precisely and easily controlled in MITEE than in the PBR, so that all regions in the fuel zone can be evenly cooled. Moreover, the possibility of local “hot spots” will be greatly reduced by the excellent 2D lateral thermal conductivity in the metal matrix fuel sheets, and the elimination of any chance of local thermal instability due to changes in gas viscosity with temperature. (The latter concern is removed in MITEE by the mixing of coolant flow between the metal sheets.) 4) The startup time for MITEE can be much longer than the PBR (e.g., 20 seconds compared to 5 seconds) without compromising engine performance. The much longer startup time greatly eases demands on the reactor control system and permits a smoother, more controlled temperature rise in the fuel zone. 5)The individual pressure tube nozzle arrangement in the MITEE design for each fuel element greatly simplifies reactor construction by eliminating the need for a large diameter, high strength pressure vessel, with an attached, separately cooled nozzle, which was used in the design of the PBR. 6) The much lower power level for MITEE (75 MW compared to 1000 MW for the PBR) greatly eases the testing requirements, both in terms of testing the complete reactor assembly, and also in testing individual fuel elements. Each of the 37 fuel elements in MITEE has a total thermal power of only 2 MW, compared to almost 30 MW for the PBR. 7) The thermal hydraulic performance of the MITEE fuel elements can be fully tested and validated in a non-nuclear mode, using electrical heating of the metal matrix fuel sheets to simulate the nuclear heating process. Nuclear testing of the final fuel element design would still need to be carried out to confirm and validate the design, but the long lead times and great expense of nuclear tests can be largely bypassed with MITEE. With the PBR, in contrast, it is not feasible to electrically heat the fuel elements to simulate nuclear heating. 8) The primary mission for the PBR was as a high performance second stage for existing first stage boosters, with nuclear startup before achieving orbit. As a result, extensive ground testing of the full-up nuclear engine was considered necessary to assure safety, reliability, and mission performance. The associated ground test facility was very costly and required a long lead time. Full containment and assured safety were very strong drivers in developing the facility. Since the MITEE engine would only startup in an already achieved high orbit, it appears possible to test its operation in space, rather than in a ground based facility. Moreover, since the fabrication cost of MITEE test units should be modest and the launch vehicle costs relatively low, it appears much more cost effective to test in space rather than build a new dedicated ground test facility. It should be no harder to acquire the appropriate data from a space based MITEE test than from a ground test. Such tests can probably be carried out more quickly than in a ground facility. 9) At the time of the PBR development program, the nuclear rocket test facilities in the FSU were not accessible for testing a US nuclear rocket design. The FSU had extensive facilities for nuclear testing of single and multiple fuel element assemblies under realistic operational conditions. With the end of the Cold War, these facilities are now available to the US and could be used in a cooperative program to develop a MITEE engine. Much of the nuclear testing and material development could be carried out using these facilities, at considerably lower cost than in the US.

With the above as background, a 6 year development program for MITEE has been examined. The program, would be divided into 3 phases, each 2 years in length: 1) Phase 1 - Component Development and Testing, 2) Phase 2 - Component and Assembly Validation, and 3) Phase 3 - Operational Testing of MITEE Engines. At the completion of Phase 3, the MITEE engine would have been validated as mission ready, and could be incorporated into a variety of space exploration missions.

A substantial portion of the MITEE development program would be carried out cooperatively with Russia and other nations of the FSU, using their existing facilities. In particular, their efforts would probably be concentrated in the development of the metal matrix cermet fuel and other reactor materials (e.g., hot and cold frits, nozzles, moderator) and the nuclear testing of prototype fuel elements (single and multiple, as appropriate).

Phase 3 operational testing is based on testing 4 MITEE engines in high orbit. Two engines would be launched on each of two boosters (LMLV or Delta) to give the total of 4 engines. The engines would be tested sequentially, with information from previous tests used to help guide the test sequence on the next engine. The engines could be identical or modified somewhat to test different versions or different operational conditions. For example, one could test an engine at 2750 K outlet temperature (I_{SP} of 900 seconds) and a second engine at 3000 K outlet temperature (I_{SP} of 1000 seconds). Depending on test results, one could then decide on whether to limit MITEE operation to 2750 K for the first generation of missions, or go to 3000 K. The 2 launch vehicles would be spaced-in-time approximately 9 months to a year apart so that results from the first 2 MITEE engine tests could be used, if desired, to modify the next 2 MITEE engines scheduled for testing.

The estimated total program cost is 800 million dollars, with the Phase 3 testing accounting for 50% of the total. These estimates are of course very rough, and would have to be developed in much more detail before starting a MITEE development program. However, the launch cost for Titan IV is approximately 400 million dollars. Other launch systems, while not quite as costly, are still very expensive. Thus, a few MITEE missions would more than pay for development cost by the ability to greatly reduce the cost of the launch vehicles needed to carry out the missions.

7.4 Earth-Mars-Earth Transport

Developing a robust and reliable Earth-Mars-Earth transport infrastructure that is based on the use of H_2 propellant manufactured on and conveyed from Mars will comprise the principal R&D effort and require the majority of the R&D funding in a Mars colony program. New types of spacecraft would have to be designed, constructed, and tested with the capability to transport passengers and cargo to and from Mars, transferring propellant from the Martian surface to Mars orbit, and storing propellant on orbital depots, at both Mars and Earth.

The spacecraft R&D program for the colony concept would essentially be an extension of what would be necessary for the conventional manned Mars missions. Both will require passenger and cargo transport spacecraft. The colony approach would require the condition of a Mars fueling shuttle and orbital propellant depots.

More detailed study is needed to determine the additional spacecraft R&D cost for the colony concept, as compared to that for the conventional individual mission approach. Since the fueling shuttle is a relatively simple vehicle, and the orbital depots would use spent space shuttle external tanks, it appears that the additional R&D cost should be somewhat less than that for the R&D for the cargo and passenger spacecraft.

7.5 Mars Exploration Vehicles

The R&D effort to develop exploration vehicles for the Mars colony concept will have a somewhat different philosophy than the R&D effort for the Earth-Mars-Earth spacecraft. For the latter, an evolutionary type R&D, in which early vehicles do not deliver the desired performance, is not practical. The interplanetary spacecraft must perform as required, or the mission will fail. Major changes and improvements to the spacecraft are difficult and expensive.

For the Mars exploration vehicles, on the other hand, the colonists can begin to explore Mars using relatively short range manned land rovers (e.g., 200 km range instead of 1000 km) and flyers (e.g., 200 km between touchdowns, rather than 1000 km), and still achieve very important and exciting scientific results.

Accordingly, the first generation of Mars exploration vehicles would probably be conservatively designed with large margins. This would greatly reduce the amount and cost of the R&D required for these first generation vehicles.

As the Mars exploration program proceeds, the capabilities of the exploration vehicles would be upgraded, enabling longer trips. Since the Mars colony would fabricate, test, and operate the exploration vehicles, it would be the principal agent to carry out additional R&D efforts on the vehicles.

8 SCHEDULE AND COST TO DEVELOP THE TECHNOLOGY REQUIRED FOR XANADU

Table 8.1 summarizes estimates for the time periods and R&D costs that would be needed to develop the technology to implement the Mars colony concept. These estimates are very rough and preliminary. A more detailed study is required in order to obtain greater accuracy.

The spacecraft R&D cost represents **b** of the total R&D cost. Spread over a 15 year period, the total 30 B$ R&D cost would amount to approximately 2 B$ per year, which appears very reasonable, given the importance of the human exploration and settlement of Mars.

The above costs only reflect technology R&D costs. Additional funding would be necessary to build and operate the various units needed to implement a Mars colony.

Table 8.1 Preliminary Estimates of the Time Periods and R&D Costs Required to Develop Technology for the Mars Colony Concept

Technology Component	R&D Time Interval (Years)	R&D Cost (Billion $)
MICE Probes	5	2
ALPH Factory	7	3
MITEE Propulsion Engine (Including Adoption for Mars Mission)	8	3
Spacecraft for Earth-Mars-Earth Transport	12	20
Mars Exploration Vehicles	10	2
	Total	30

9 SUMMARY AND CONCLUSIONS

A new approach for the large scale exploration of Mars is described. This approach would establish a permanent colony on Mars' North Polar Cap where unlimited amounts of water in the form of an extensive, thick ice sheet are readily accessible. A compact robotic factory unit, termed ALPH, would be landed on the ice sheet at the colony site 2 years before the first group of colonists arrived. Using a small, ultra lightweight nuclear reactor to supply heat and electric power. ALPH would manufacture and stockpile hundreds of tons of propellants and supplies that would be ready for use when the colonists arrived. In addition, ALPH would also create large, insulated habitats under the ice surface, in which the colonists would be fully shielded from cosmic radiation.

Ample amounts of all of the materials - propellants, fuels, air, water, plastics, and food - required for a large permanent colony would be produced by ALPH using ice together with CO_2 and N_2 from the Martian atmosphere as raw feed materials. In addition to producing all of the supplies needed by the colony for life support and a vigorous Mars exploration program. ALPH would also produce large amounts of liquid H_2 and O_2, enabling an Earth-Mars-Earth transport architecture that would not require lifting propellants from Earth. Orbital fueling depots at Mars and Earth GEO would be supplied with propellants and supplies lifted from the Mars colony. The only Earth based launch requirements that remain are to lift Mars bound colonists up to GEO orbit. Propellants and supplies for trips from GEO to Mars and return to Earth would come from Mars, taking advantage of the lower)V requirements.

A strong technology base already exists for the ALPH reactor and process units, as well as the nuclear thermal propulsion engines that would be used for the Earth-Mars-Earth architecture. The ALPH and MITEE propulsion systems can be demonstrated and ready for application within the time frame presently being considered for the initial manned missions to Mars. Based on a first manned landing in 2018, ALPH would have produced and stockpiled hundreds of tons of propellants and supplies at the North Polar landing site.

Following the first landing, the colony could rapidly build up to a mature population of ~500 persons by 2034 AD. Assuming an average turnover rate equivalent to 20% of the colony population returning to Earth every 2 years, the corresponding Earth launch requirements to sustain the colony would be only 5 habitat vehicle launches to GEO every 2 years, with each habitat weighing ~100 tons and carrying 20 persons.

In conclusion, the self-supporting Mars colony exploration approach has major advantages over the conventional individual mission approach. These include:

- Much greater Mars exploration capability
- Much lower risk, for both the astronauts and the mission

- Greatly reduced Earth launch requirements
- Much better living conditions on Mars
- Ability to use Mars as a base for exploration of the outer solar system.

Based on these advantages, further investigation of the Mars colony approach appears desirable, including R&D on the key technology elements.

Table 3.2.1 MICE Reactor Parameters

Reactor Thermal Power Operating Range, KW(th)	20 to 200 (depends on desired melt rate)
Core Diameter, cm	28.6
Core Height, cm	28.6
Core Moderator	Lithium-7 Hydride (^{7}LiH)
Nuclear Fuel	Uranium Hydride Homogeneously Mixed with ^{7}LiH Moderator
U-235 Loading, kilograms	2.18 (2.33 kg total uranium [U-235 plus U-238])
Coolant	Water
Core Geometry	Stainless Steel Coolant Tubes in Solid Lithium-7 Hydride Moderator Block
Number of Coolant Tubes	169
Diameter of Coolant Tube, cm	0.635
Coolant Tube Wall Thickness, cm	0.10
Coolant Tube Pitch/Diameter Ratio	3.0 (hexagonal lattice)
Coolant Tube Pitch, cm	1.905
Reflector	
Material	Lithium-7 hydrid
Radial Thickness, cm	5.0
Axial Thickness, cm	5.0
Reactor Mass Budget, kilograms	
Coolant	0.72
Coolant Tubes	6.32
Fuel/Moderator	13.29
Radial Reflector	12.30
Axial Reflector	10.75
Control Fods	5.00
	48.41
Multiplication Factor W/Coolant, k_{eff}	
Control Rods not Inserted	1.067
7 Control Rods Inserted	1.019
13 Control Rods Inserted	0.978

Table 3.2.2 MICE Thermal and Electrical Power System Parameters

Basis = 200 KW(th) Operation

<u>Reactor Coolant System</u>	
Low temperature tubes, inlet temp	30/C
Low temperature tubes, outlet temp	50/C
High temperature tubes, outlet temp	250/C
Flow velocity in low temp tubes	1 meter/sec
Heat flux in low temp tubes	20 watts/cm^2
Film)T in low temp tubes	30/C
<u>Warm Water Jet System</u>	
Melt water intake temperature	10/C
Water jet outlet temperature	20/C
Water jet flow rate	5 liters/ec
Film)T in low temp tubes	30/C (2 sides of
Heat exchange tube OD	tubes)
Tube watt thickness and material	0.7 cm
Heat exchanger volume	0.10 cm, Be
Heat exchanger weight	10 liters
	5 kg
<u>Power Generation System</u>	
Electric power output	3 KW(e)
Turbo/generator mechanical efficiency	80%
Steam fraction in outlet coolant	30%
Turbine inlet pressure	40 atm
Turbine outlet pressure	1 atm
Thermal cycle efficiency [w(e)/w(th)]	20%
Weight of turbine plus generator	5 kg

Table 3.2.3 MICE Mass Budget (Data Only Mission)

Component		Mass, Kilograms
Reactor (core, reflector, coolant, tubes, coolant and control		48
rods)		27
Beryllium pressure vessel		3
Water jet system (tubes and valves)		7
Heat exchanger and steam/water separator		5
Steam turbine and electric generator [3 KW(e) system]		2
Umbilical line		50
Optical fiber communication line		5
[Be tube jacket, 10 km length MICE		50
Contingency (33%)]		197
	Subtotal	200
Lander, transmitter, and aeroshell		397
	MICE Payload	

Table 3.2.4 MICE Mission Parameters

Parameter	Option 1 Date Only	Option 2 Data Plus Sample Return
Nominal departure date	6/6/03	6/6/03
Nominal arrival date	1/2/04	1/2/04
Launch vehicle	Delta II	Delta II
)V, LEO departure, km/s	3.6	3.6
MICE payload, kg	400	600
Mass of return samples, kg	---	200
IMLEO, kg	2500	5000
Mass of H_2/O_2 propellant in LEO, kg	1400	2800
Mass of H_2/O_2 propellant produced on Mar's ice cap, kg	---	3600

Table 4.2.1 Principal ALPH Parameters for Initial Landing at Colony Site

# of ALPH units at outpost	2
Thermal power of each ALPH reactor	2.67 MW(th)
Thermal cycle efficiency (including generator and transmission losses)	20%
Outpost electric power from each ALPH unit	535 kW(e)
Outlet temperature/pressure of ALPH water coolant	550 K/70 atm
Inlet temperature/pressure of ALPH steam turbine	520 K/37.1 atm
Condenser temperature/pressure of ALPH steam turbine	330 K/0.172 atm
Turbine isentropic efficiency (including pump power requirements)	70%
Generator efficiency	95%
Transmission efficiency	98%

Table 4.9.1 Storage and Habitat Cavities at Colony Site

Cavity Parameters								
			Diameter (m)					
Purpose	# Cavities	Shape	OD	ID (1)	Height (m)	Usable (2) Volume (m^3)	Amt Stored (tons)	Fill (2) Fraction
Habitat	4	Domed Cylinder	9.3	9.0	5.0	320	---	---
Liquid H_2 Storage	4		10.0	8.5	15.0	850	40	67%
Liquid O_2 Storage	4		7.3	7.0	15.0	580	420	
Liquid CH_4 Storage	4 Cylinder		3.3	3.0	5.0	35	15	
Methanol Storage	4		3.0	2.7	5.0	39	15	

(1) Difference between cavity OD and ID values is due to thermal insulation layer.
(2) Usable volume calculated on basis of cavity ID; fill fraction is ~**b** for each cavity.
(3) Depth shown is distance of cavity top below surface.

Table 4.9.2 Materials Stockpile at Colony Site
(Basis: 2 ALPH Units)

Amounts Available 11 Months After Touchdown	Quantity of Material, Metric Tons					
	Liquid H_2	Liquid O_2	Liquid CH_4	Methanol	Plastic	Food
ALPH Unit #1 - Cavity #1	40	420	15	15	1	
ALPH Unit #2 - Cavity #2	40	420	15	15	7.5	1
Sub Total	80	840	30	30	15.0	2
Additional Amounts Available 20 Months After Touchdown						
ALPH Unit #1 - Cavity #2	40	420	15	15	7.5	1
ALPH Unit #2 - Cavity #4	40	420	15	15	7.5	1
Sub Total	80	840	30	30	15.0	2
All Cavities - Grand Total	**160**	**1680**	**60**	**60**	**30.0**	**4**

Table 4.9.3 Mass Budget for One ALPH Lander Unit

Component	Mass (kg)
Reactor/Power System	
Fuel elements (22)	280
Control rods (3), drives, and structure	50
Water coolant	Supplied from Mars Ice
Circulator, steam gen., condenser and pump	90
Steam turbine/elec. Gen.	100
Pressure vessel (Titanium)	330
Controls, pipes, cables, etc.	30
Melt shell (Beryllium)	30
Sub Total	910
Secondary, Thermal Melt Lines (10 Total)	
[H_2 (2), O_2 (2), CH_4 (2), CH_3OH (2), Habitat (2)]	
Warm water pipes (3/lines)	20
Process fluid pipe (3/lines)	100
Gas pipes for balloon Ins (3/lines)	20
Melt shells (1/line)	100
Collapsible balloons (1/line)	1800
Sub Total	2040
Process Units	
Electrolyzers/power cond.	350
Liquefiers/Refrigerators	150
Methanator	50
Plastic polymizer unit	100
Sub Total	650
Lander Structure (10% of Total)	500
Contingency (20% of Total)	1000
Total	5100

Table 5.1.1 Mars Propellant Flow: Requirements for a Steady State Mars Colony

Basis: Mature colony of 500 persons   Turnover rate of 20% every 2 years
(100 persons to Mars, 100 persons to Earth)   5 habitat trips out every 2 years
5 habitat trips back every 2 years   Propellant requirements normalized to an annual basis
5/1 mixture ratio for H_2/O_2 engines

	Liquid H_2 (Metric Tons/Yr)	Liquid O_2 (Metric Tons/Yr)
1. Liquid H_2 transported to GEO depot for 5 habitat trips per 2 years	175	---
2. Liquid H_2 required by NTCPV to transport liquid H_2 to GEO depot (2 NTCPV trips per 2 years)	200	---
3. Liquid H_2 in Mars depot to fuel cyclers for habitat trips back to Earth	175	---
4. Fuel for H_2/O_2 engines to lift habitats from colony to Mars depot (5 habitat trips per 2 years)	45	230
5. Fuel for H_2/O_2 engines on fueling shuttle to lift liquid H_2 to Mars depot	240	1200
Total produced at colony	835	1430

Table 5.1.2 Earth-Mars-Earth Transport Architecture for Passenger GEO Base

1. Habitat @ 93 tons is lifted to GEO from LEO by 51 ton OTV. Total payload (Habitat Plus OT)V lifted to LEO is 144 tons (Saturn V Booster)
2. Habitat rendezvous with baseline cycler (1st stage no nuclear, 2nd stage chemical) and fueling depot (comprised of spent shuttle tanks in GEO). Cycler has been refueled and refitted with new MITEE for 1st stage engine.
3. After Cycler is fueled, the habitat/cycler leaves for Mars.)V = 3.7 km/sec and trip time is 105 days.
4. After 105 day interplanetary coast, the Habitat separates from the cycler upon arrival at Mars. The Habitat aerobrakes and performs a 2 km/sec)V burn for controlled landing on Mars.
5. The Cycler then performs a 4.0 km/sec)V burn for Mars orbit capture.
6. Cycler rendezvous with the fueling depot in Mars orbit. The fueling depot is comprised of Shuttle external tanks sent from Earth. Cycler is refueled and refitted with new MITEE engine.
7. For return to Earth, the Habitat is refueled on the Martian surface. It then performs a single stage to Mars orbit trip.
8. Habitat rendezvous with the Cycler at the fueling depot in Mars orbit
9. The combined Habitat-Cycler performs a)V burn of 4.7 km/sec and departs for Earth. Trip time is 120 days.
10. Upon arrival at Earth's GEO, the Habitat separates from the Cycler and performs a 2 km/sec burn to decrease the re-entry velocity to ~11 km/sec (Apollo-type re-entry) for landing on Earth.
11. Cycler performs a 3.7 km/sec burn at GEO for orbit insertion.
12. Cycler rendezvous with the GEO fueling depot where the Cycler will be refueled and retrofitted with a new MITEE engine. The cycle repeats again starting with 1.

Table 5.1.3 Earth-Mars-Earth Transport Architecture for Cargo GEO Base

1. Fueling Shuttle lifts off from Martian surface with 55 ton propellant payload. Total initial mass is 210 metric tons.) V to achieve orbital velocity $\simeq$ 5.0 km/sec.
2. Fueling Shuttle rendezvous with fueling depot (comprised of multiple space shuttle external tanks) in Mars orbit to transfer the 55 ton cargo of H_2 propellant to the fueling depot. Multiple Fueling Shuttle launches keep the fuel depot full of propellant.
3. Fueling depot transfers propellant to the Nuclear Thermal Cargo Propellant Vehicle for its round trip journey to GEO to carry H_2 propellant payload to the fuel depot at GEO. Total propellant payload is 200 metric tons and total initial mass in Martian orbit is 400 metric tons. NTCPV is refitted with 2 MITEE stages.
4. The NTCPV performs ~2.8 km/sec) V burn for a 7 month interplanetary coast to GEO using MITEE first stage which is discarded after the burn.
5. NTCPV performs a 2.7 km/sec) V burn for GEO capture using MITEE second stage which is jettisoned after the burn.
6. Cargo Propellant Vehicle transfers the 200 metric ton propellant payload to the fueling depot in GEO and is refitted with 2 MITEE stages for return to Mars after rendezvous.
7. With remaining fuel on board, the NTCPV mass is 32 metric tons. NTCPV performs a 2.9 km/sec) V burn for a 7 month return trip to Mars. MITEE first stage is discarded.
8. NTCPV performs a 2.1 km/sec) V burn for Mars orbit insertion. MITEE stage is discarded and NTCPV rendezvous with fuel depot.

Table 5.1.4 Earth-Mars-Earth Transport Architecture for Passenger LEO Base

1. Habitat @ 93 tons is lifted to LEO by a heavy lift Energia class or Saturn V-class booster.
2. Habitat rendezvous with baseline Cycler (1st stage nuclear, 2nd stage chemical) and fuel depot (comprised of Space Shuttle external tanks) in LEO. Cycler has been refueled and refitted with MITEE 1st stage.
3. After Cycler is fueled, the Habitat/Cycler departs for Mars. The)V burn is 4.6 km/sec in LEO. Trip time is 105 days total.
4. After 105 day interplanetary coast, the habitat separates from the Cycler upon arrival at Mars. The Habitat aerobrakes during re-entry and performs a 2 km/sec burn for controlled landing on the Martian surface.
5. Cycler performs a)V burn of 3.8 km/sec for Mars orbit capture.
6. Cycler rendezvous with the fuel depot (comprised of shuttle external tanks sent from Earth) in Mars orbit Cycler is refueled and refitted with new MITEE 1st stage.
7. For return to Earth, the Habitat is refueled on the Martian surface and performs a single-stage trip to low Mars orbit.
8. Habitat rendezvous with the Cycler at the fuel depot in Mars orbit.
9. The combined Habitat/Cycler performs a)V burn of 4.2 km/sec for departure to Earth. Trip time is 120 days.
10. Upon arrival at Earth's LEO, the Habitat separates from the Cycler and performs a 2 km/sec burn to decrease re-entry velocity to ~11 km/sec (Apollo-type re-entry) for landing on Earth.
11. Cycler performs a)V burn of 4.7 km/sec at LEO for orbit insertion.
12. Cycler rendezvous with the fuel depot (comprised of space shuttle tanks) where the cycler is refueled and refitted with a new MITEE first stage engine. The entire cycle repeats again with 1.

Table 5.1.5 Earth-Mars-Earth Transport Architecture for Cargo LEO Base

1. Fueling Shuttle lifts off Mars surface with 55 ton propellant payload. Initial mass is 210 metric tons.)V to achieve orbital velocity is 5.0 km/sec.
2. Fueling Shuttle rendezvous with fuel depot (comprised of multiple space shuttle tanks) in Mars orbit to transfer the 55 ton propellant cargo. Multiple Fueling Shuttle launches keep the fuel depot full of propellant.
3. Fuel depot transfers propellant fuel to the Cargo Propellant Vehicle (CPV) for a round trip to LEO and payload transfer to the fuel depot at LEO. Total propellant payload is 84 metric tons and total initial mass in Martian orbit is 400 metric tons. The CPV has a MITEE first stage and a reusable chemical second stage.
4. The CPV performs a 2.8 km/sec)V burn for a 7 month interplanetary coast to LEO MITEE first stage which is discarded after the burn.
5. CPV performs a 3.8 km/sec)V burn for LEO capture using the chemical second stage engine.
6. CPV transfers the 84 metric ton propellant payload to the fuel depot in LEO and is refitted with MITEE 1st stage engine.
7. With remaining fuel on board, the CPV mass is 43 metric tons. The CPV performs a 4.0 km/sec)V burn for a 7 month return trip to Mars, MITEE first stage is discarded.
8. CPV performs a 2.1 km/sec)V burn for Mars orbit insertion using the restartable chemical second stage engine and the CPV rendezvous with the fueling depot.

Table 5.2.1 MITEE Nuclear Engine Parameters

Reactor power	75 MW(th)
Coolant pressure	70 atm
Outlet temperature	3000 K
Power density in fuel elements	10 MW / liter
Moderator / reflector	^{7}LiH
Core / reflector OD	39 / 50 cm
Number fuel elements / reflector elements	37 / 24
U-235 critical mass	23 kilograms
Keff	1.07
Reactor mass	100 kg
Auxiliary mass	36 kg
Contingency	64 kg
Total engine mass	200 kg
Thrust	17,000 Newtons

Table 5.2.2 Dimensions for Selected MITEE Reactor Configurations

^{235}U Fueled Cases and 75 MW

Case Pitch/Diameter Pitch (cm) Core OD (cm) Fuel
Thickness (cm) Reactor OD (cm)

1	1.5	4.53	31.71	1.013	40.77
2	1.5	4.53	31.71	1.013	40.77
3	2.0	5.532	38.724	0.886	49.788
4	2.0	5.532	38.724	0.886	49.788
5	2.5	6.465	45.255	0.796	58.185
6	2.5	6.465	45.255	0.796	58.185
7	3.0	7.35	51.45	0.728	66.15
8	3.0	7.35	51.45	0.728	66.15
		^{233}U Fueled Cases and 50 MW			
9	1.5	3.939	27.573	0.907	35.451
10	2.0	4.804	33.628	0.795	43.236
11	2.5	5.61	39.27	0.716	50.49
12	3.0	6.372	44.604	0.656	57.348

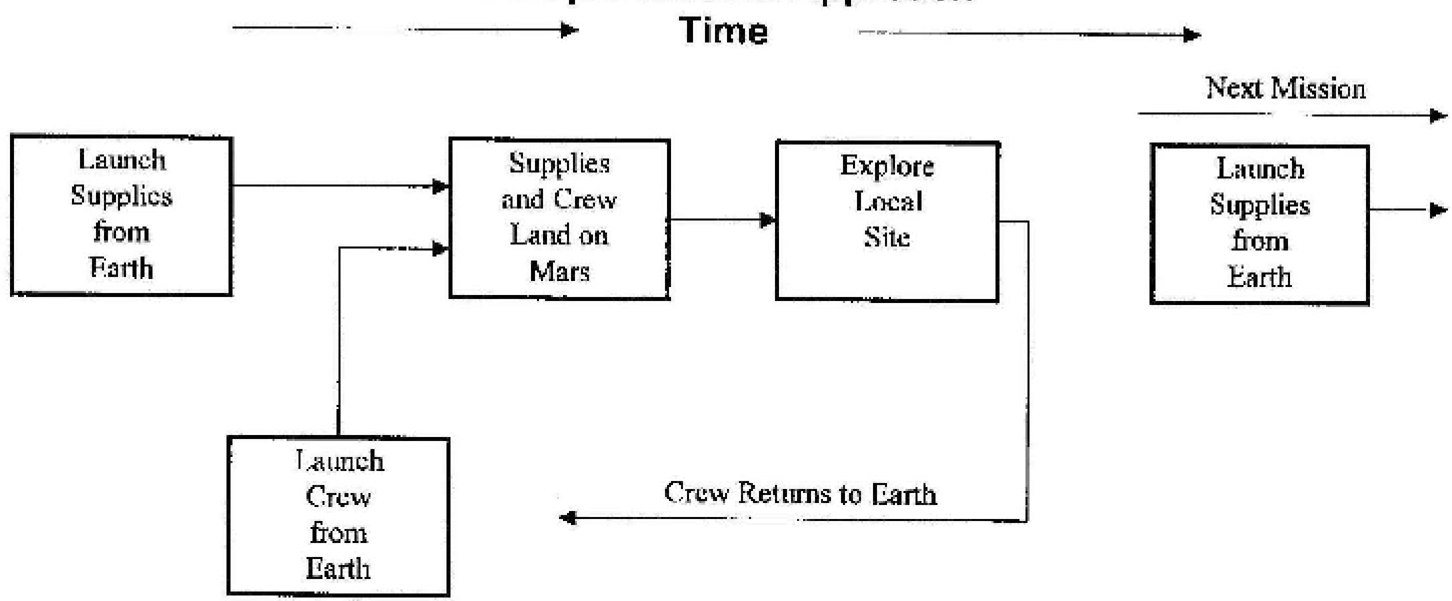
Table 6.3.1 ALPH Production Rate for Xanadu Colony

Basis: Average yearly production rate Steady state colony of 500 persons 20% turnover every 2 years

Total reactor thermal power		60 MW (th)
Total electric generation		12 MW (e)
Number of ALPH reactors (10 MW[th])		6
H_2 production, metric tons per year		
Liquid H_2 for Earth-Mars-Earth transport		835
H_2 for CH_4 and CH_3OH fuel		40
H_2 for plastics		80
H_2 for food substrates		90
H_2 for stockpile (30%)		300
	Total	1345
O_2 production, Metric tons per year		
Liquid O_2 for Earth-Mars-Earth transport		1430
O_2 for breathable air		80
O_2 for combustible fuels		800
O_2 for plastics and food		100
O_2 for stockpile (50%)		1200
O_2 surplus (discarded)		8500
	Total used	3610
General supplies, metric tons per year		
Breathable air (80% N_2, 20% O_2)		400
Water for life support		18,000
CH_4 for exploration		15
Fuels for colony		180
Plastics		500
Food (including 50% stockpile)		270
Electric power for life support		2 MW(e)
Space heat for life support		12 MW(th)

Figure 1.1

Potential Approaches for Manned Exploration of Mars
Multiple Mission Approach



Limitations/Constraints

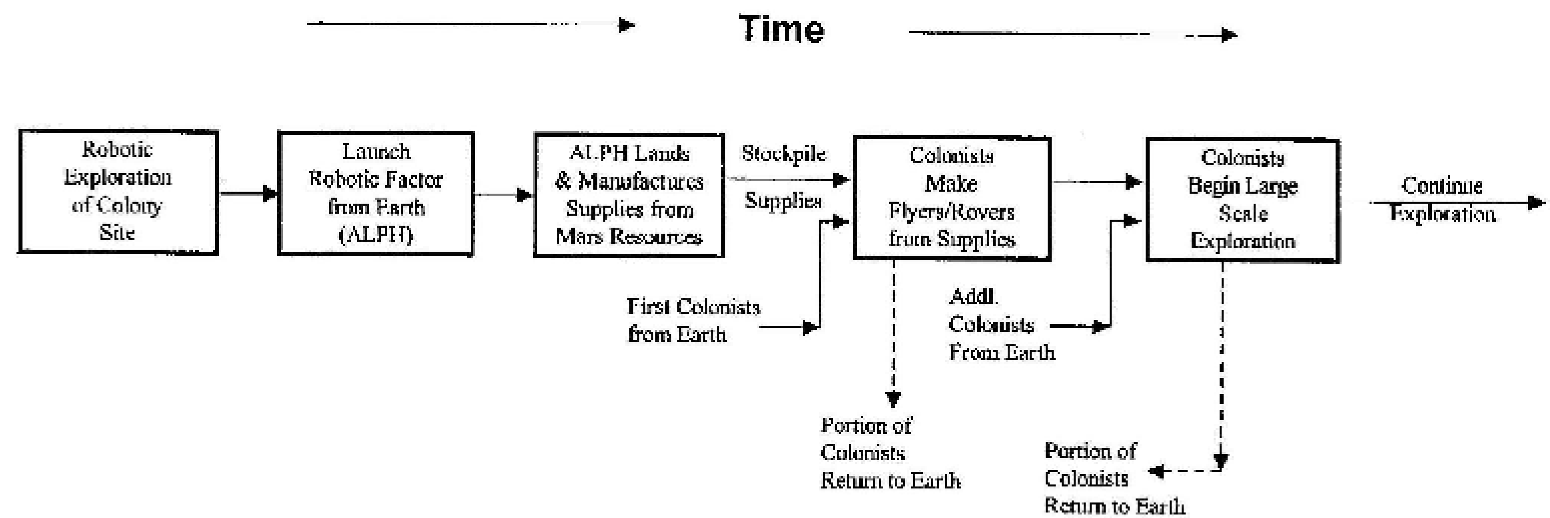
- $\geq$ 500 Tons IMLEO required per mission
- Minimal use of Martian resources - most supplies come from Earth
- Local exploration of a few sites - no broad exploration program
- Slow pace of exploration
- Safety margins are limited due to mass constraints
- Mars cannot serve as a base for exploration of the outer solar system

Figure 1.2

Potential Approaches for Manned Exploration of Mars

(continued)

Mars Colony Approach



Advantages

- Colony is largely self sustaining with regard to supplies (propellants, fuels, air, construction materials, food, etc.)
- Minimal material needed from Earth once ALPH factories start operating
- Enables broad and rapid exploration program
- Robust colony with high margin of safety
- Propellant from Mars enables increased transport of colonists from Earth
- Mars can be base for exploration of outer solar system

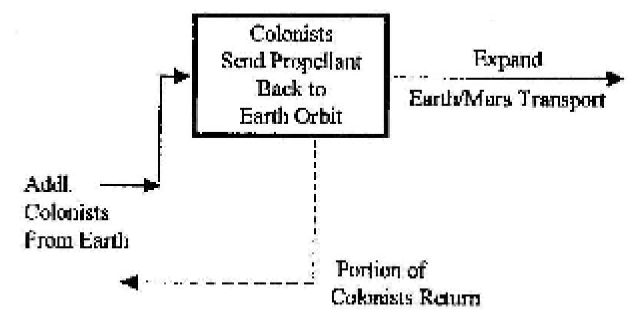


Figure 2.1

Advantages of the North Polar Cap as a Site for a Mars Colony

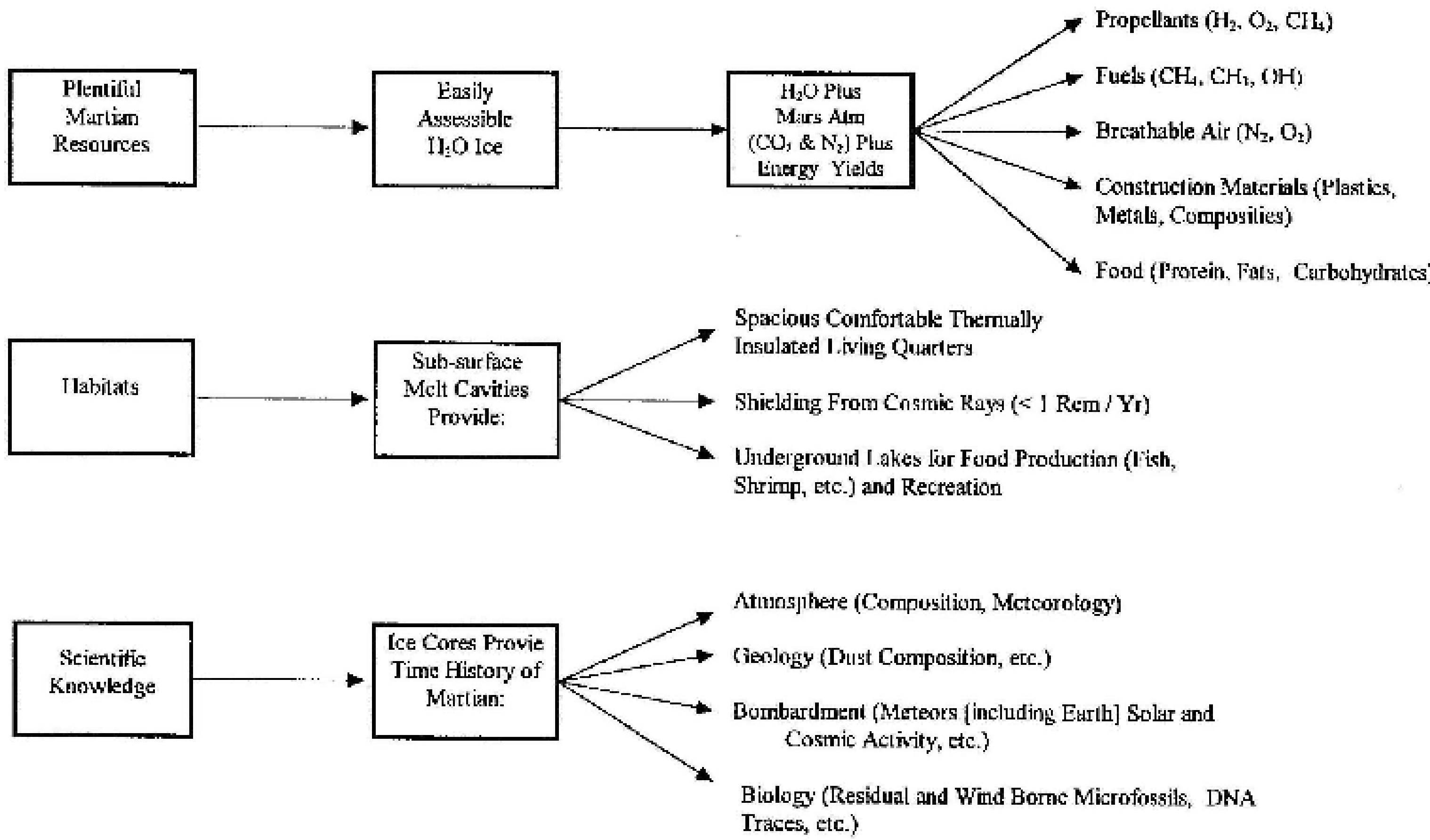


Figure 2.2

Key Technology Elements for a Mars Colony

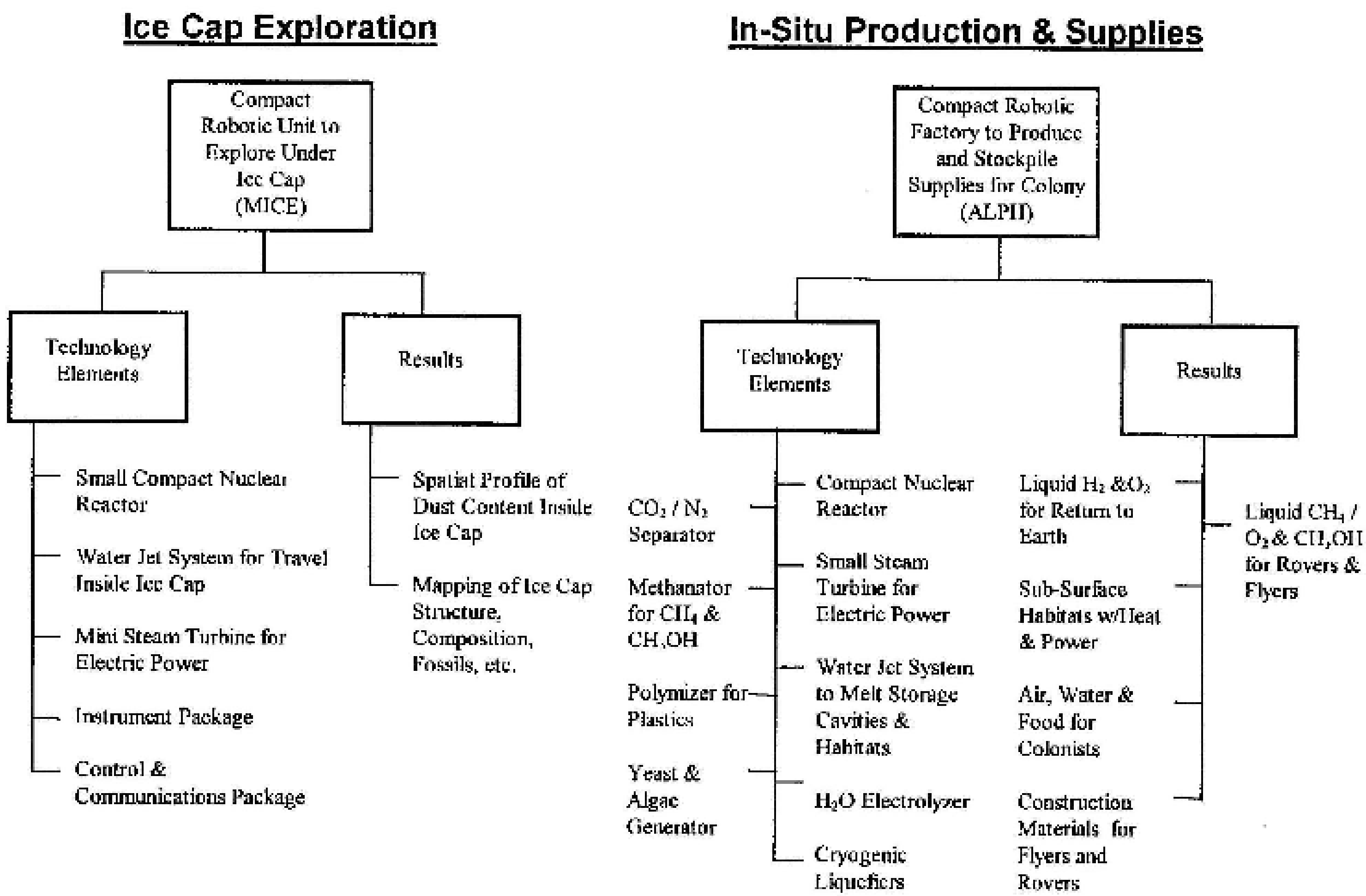


Figure 2.2 (continued)

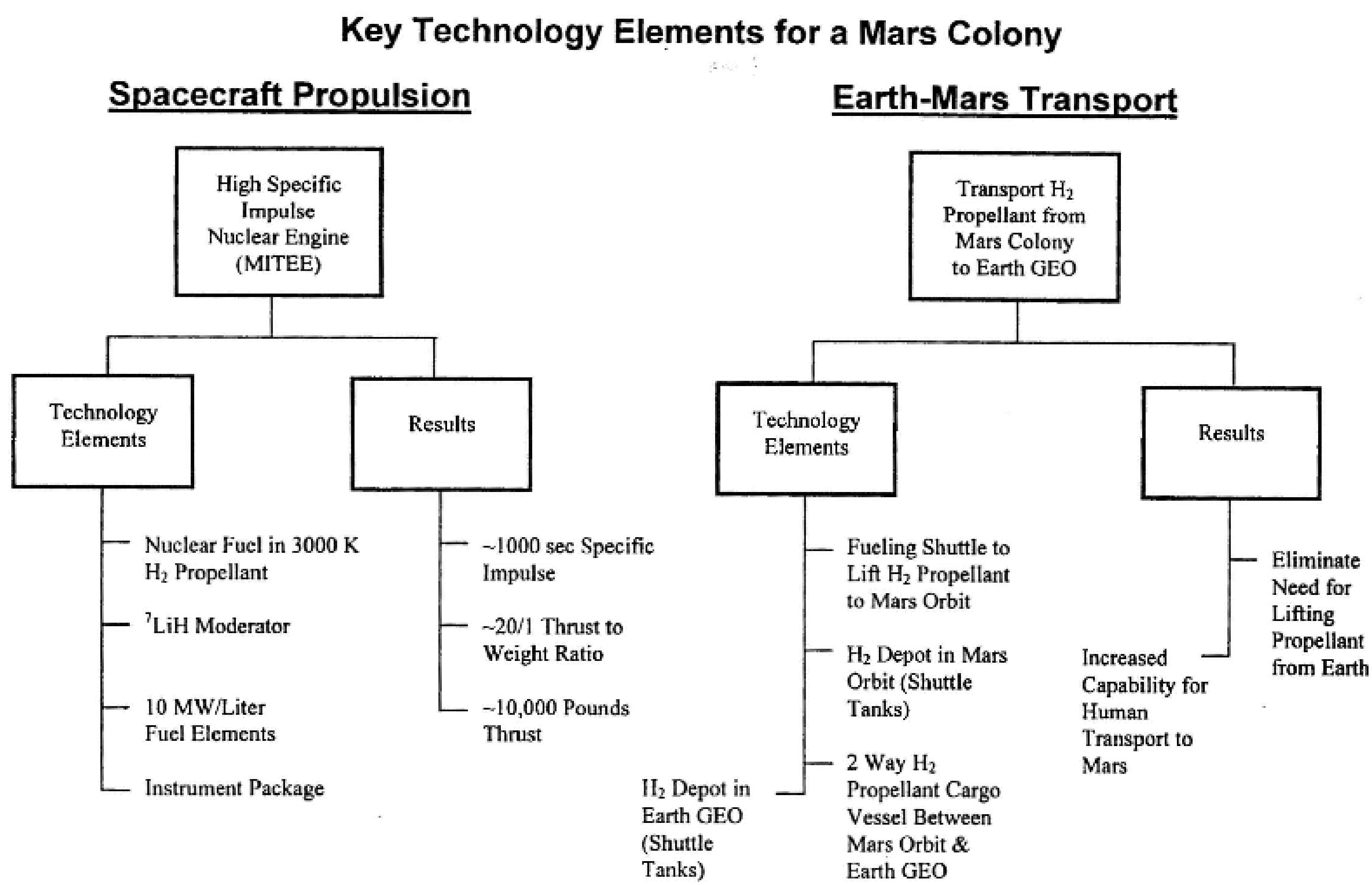


Figure 2.3

Road Map for Establishment of a Mars Colony on the North Polar Cap

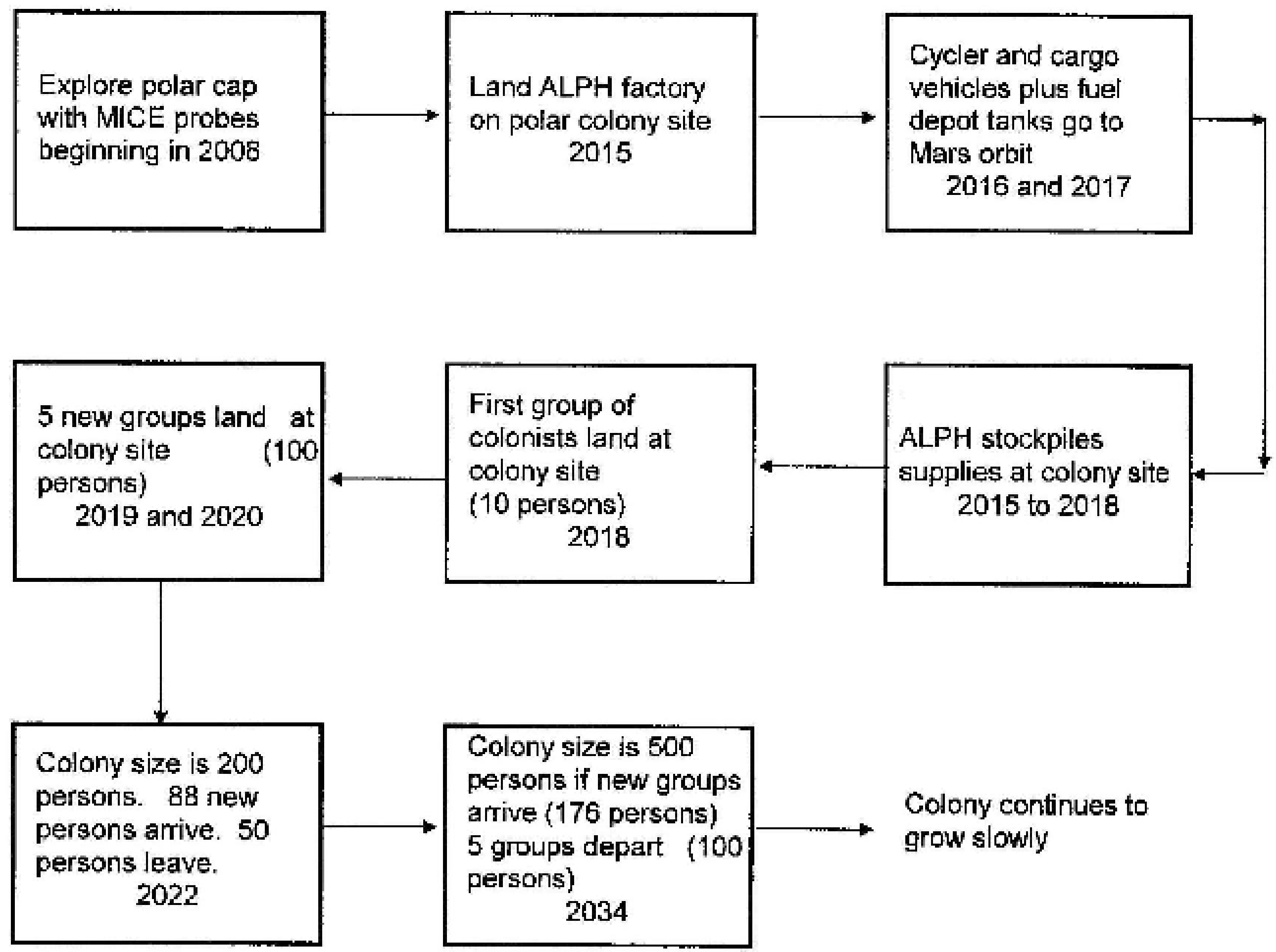


Figure 3.1.1

Criteria for Selection of a North Polar Colony Site

- Broad, flat, smooth landing area
  - No wind carved erosion gullies or layered strata
  - Wide margin for landing errors

- Competent, relatively pure H_2O ice structure
  - Low dust content in ice
  - No major dust layers or discontinuities below the surface
  - Low trapped CO_2 content in ice

- Maximize usefulness as base for Mars exploration
  - Scientifically significant sub-surface structure
  - Ready access to non-polar regions
  - Minimize potential for dust storms

Figure 3.2.1

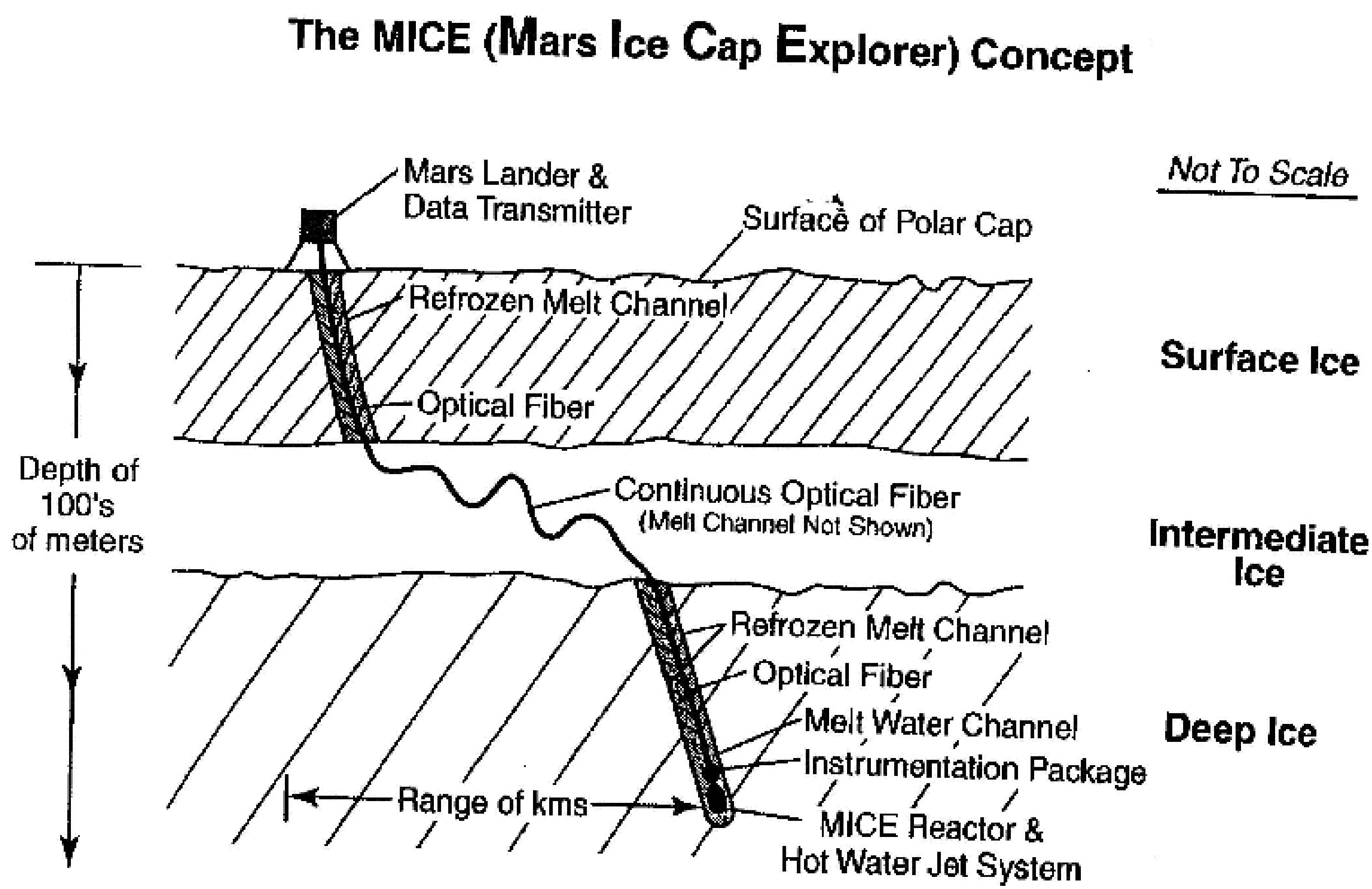
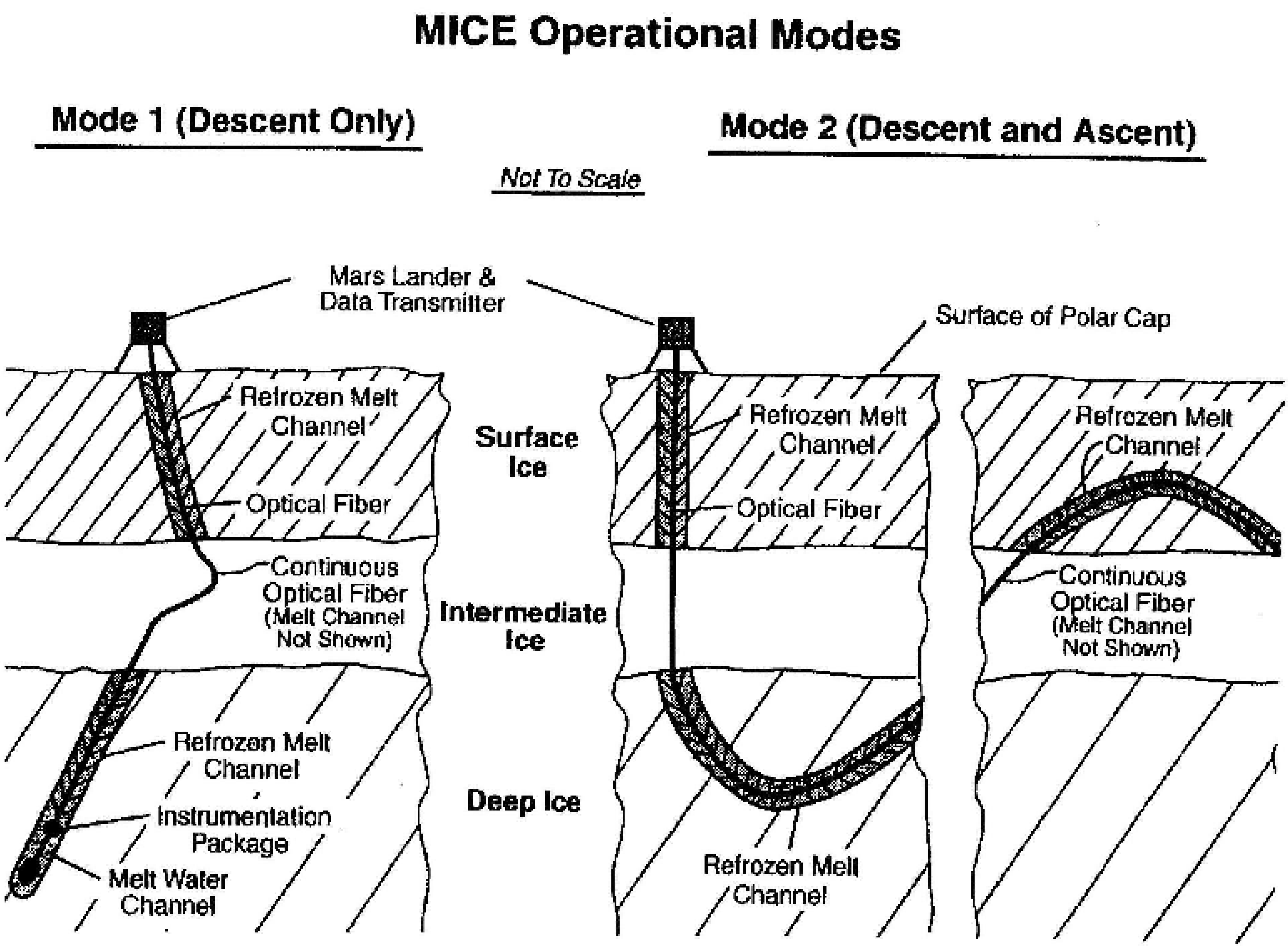

The MICE (Mars Ice Cap Explorer) Concept
Mars Lander & Data Transmitter
Surface of Polar Cap
Not To Scale
Refrozen Melt Channel
Optical Fiber
Surface Ice
Depth of 100's of meters
Continuous Optical Fiber
(Melt Channel Not Shown)
Intermediate Ice
Refrozen Melt Channel
Optical Fiber
Melt Water Channel
Instrumentation Package
Deep Ice
Range of kms
MICE Reactor & Hot Water Jet System

Figure 3.2.2



MICE Operational Modes
Mode 1 (Descent Only)
Mode 2 (Descent and Ascent)
Not To Scale
Mars Lander & Data Transmitter
Surface of Polar Cap
Refrozen Melt Channel
Optical Fiber
Continuous Optical Fiber (Melt Channel Not Shown)
Refrozen Melt Channel
Instrumentation Package
Melt Water Channel
Surface Ice
Intermediate Ice
Deep Ice
Refrozen Melt Channel
Optical Fiber
Refrozen Melt Channel
Refrozen Melt Channel
Continuous Optical Fiber (Melt Channel Not Shown)

Figure 3.2.3

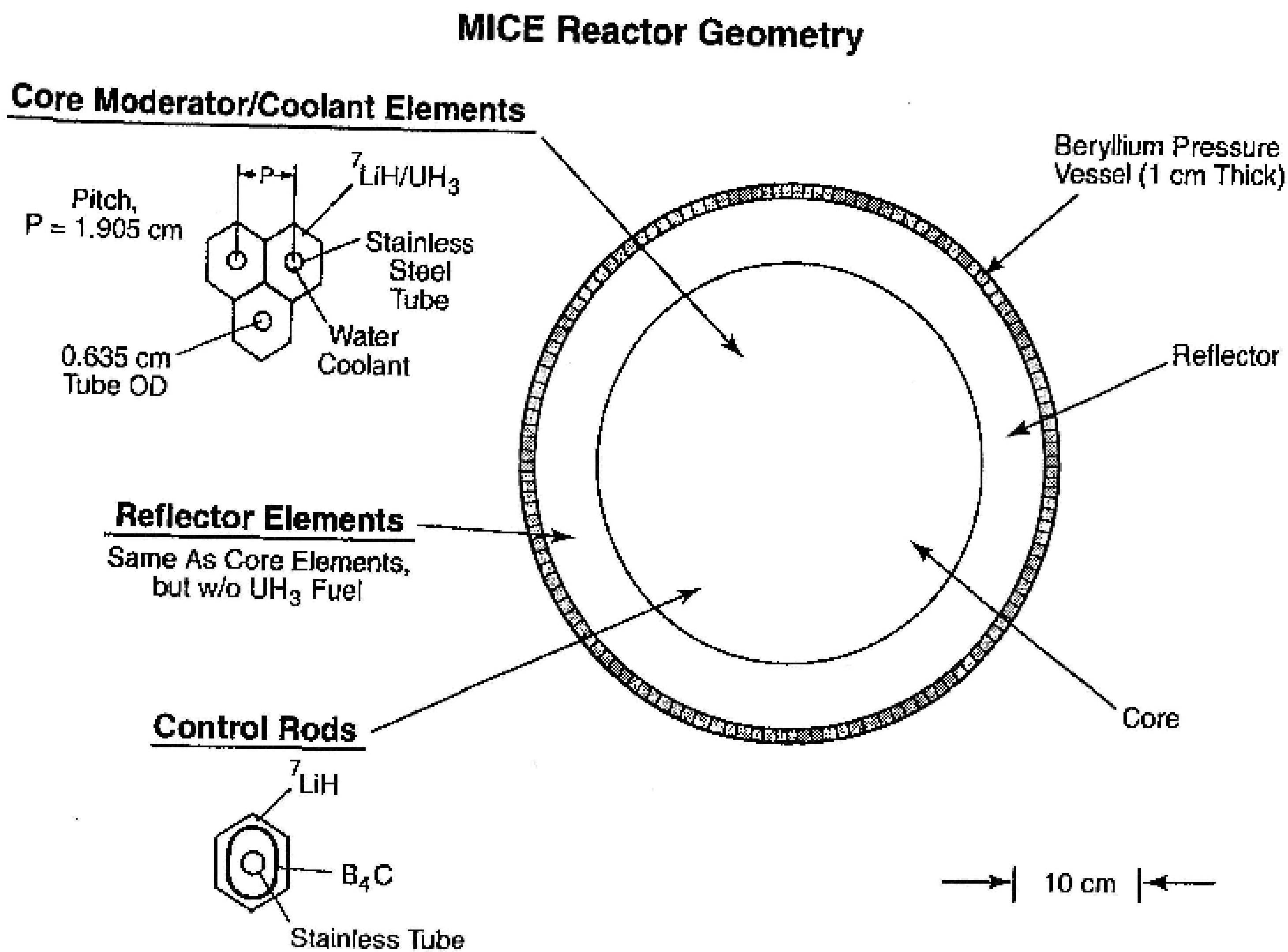

MICE Reactor Geometry
Core Moderator/Coolant Elements
P
$^{7}LiH/UH_3$
Pitch,
P = 1.905 cm
Stainless
Steel
Tube
Water
Coolant
0.635 cm
Tube OD
Beryllium Pressure
Vessel (1 cm Thick)
Reflector
Reflector Elements
Same As Core Elements,
but w/o UH_3 Fuel
Control Rods
Core
^{7}LiH
B_4C
Stainless Tube
10 cm

Figure 3.2.4

Multiplication Factor, K_{eff}, of MICE Reactor As A Function of Fuel Element Pitch/Diameter Ratio, U-235 Loading, Amount of Water Coolant, and Control Rod Configuration

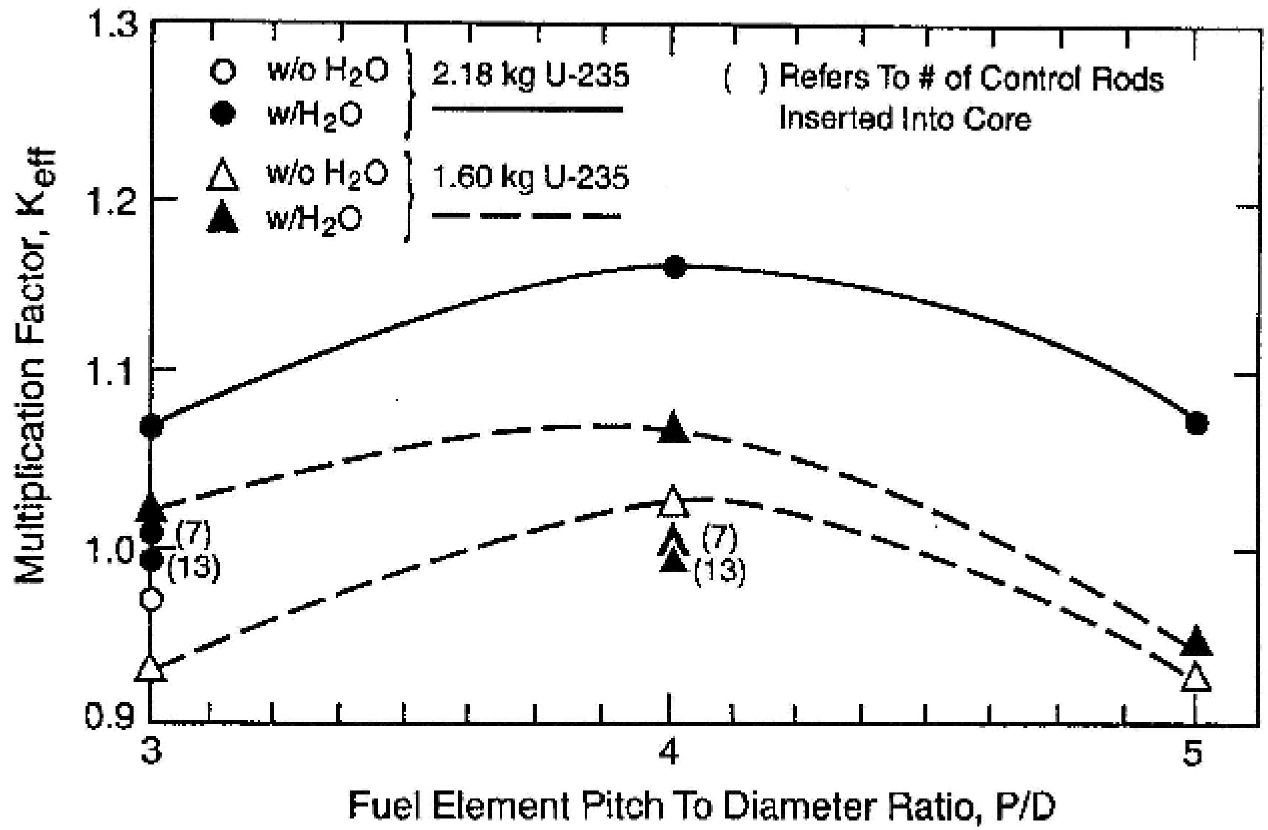


Figure 3.2.5

MICE Reactor With Instrumentation/Control System Package In Melt Channel

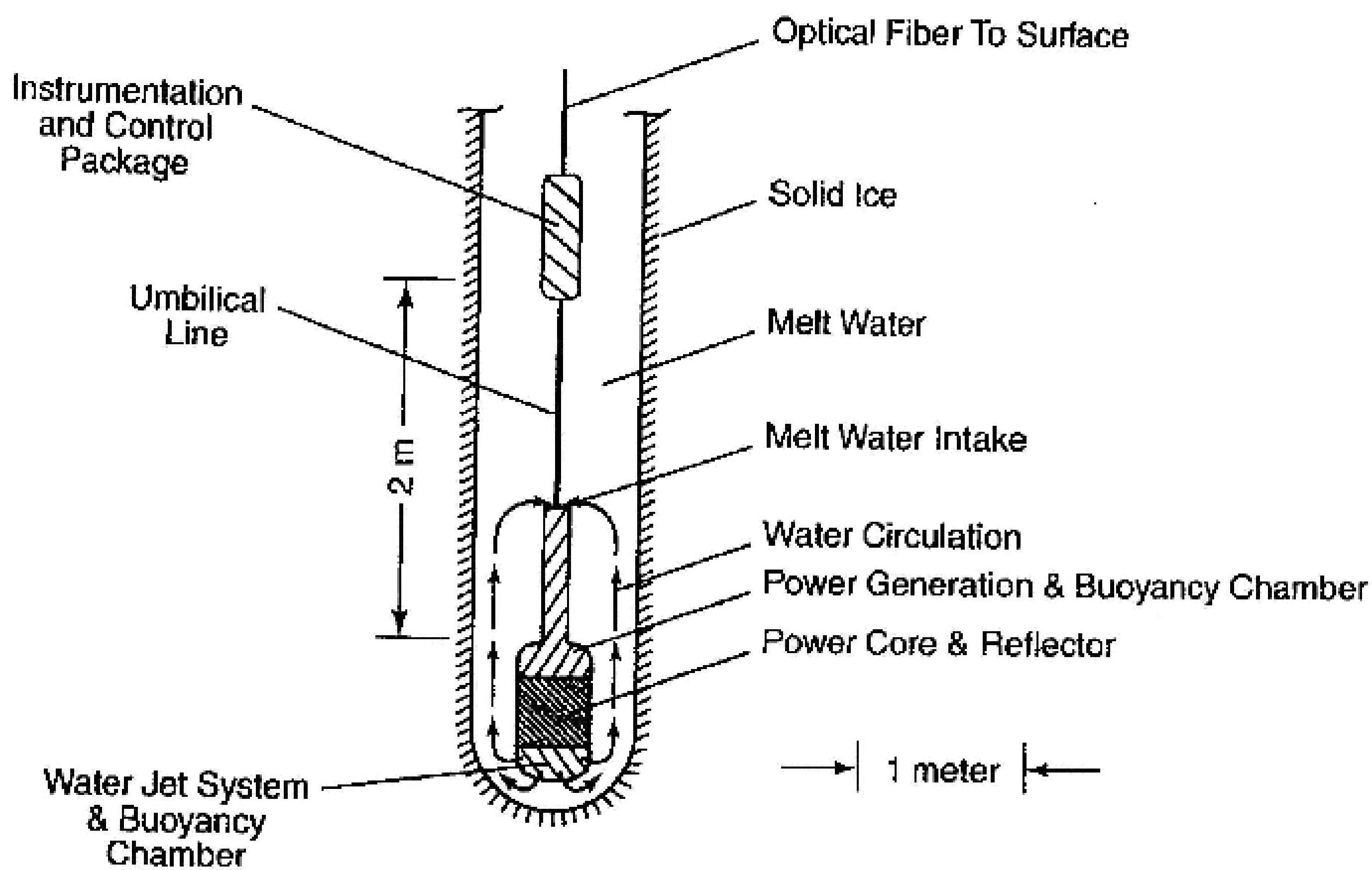


Figure 3.2.6

Radiation Dose Rate As A Function of Distance From MICE Reactor

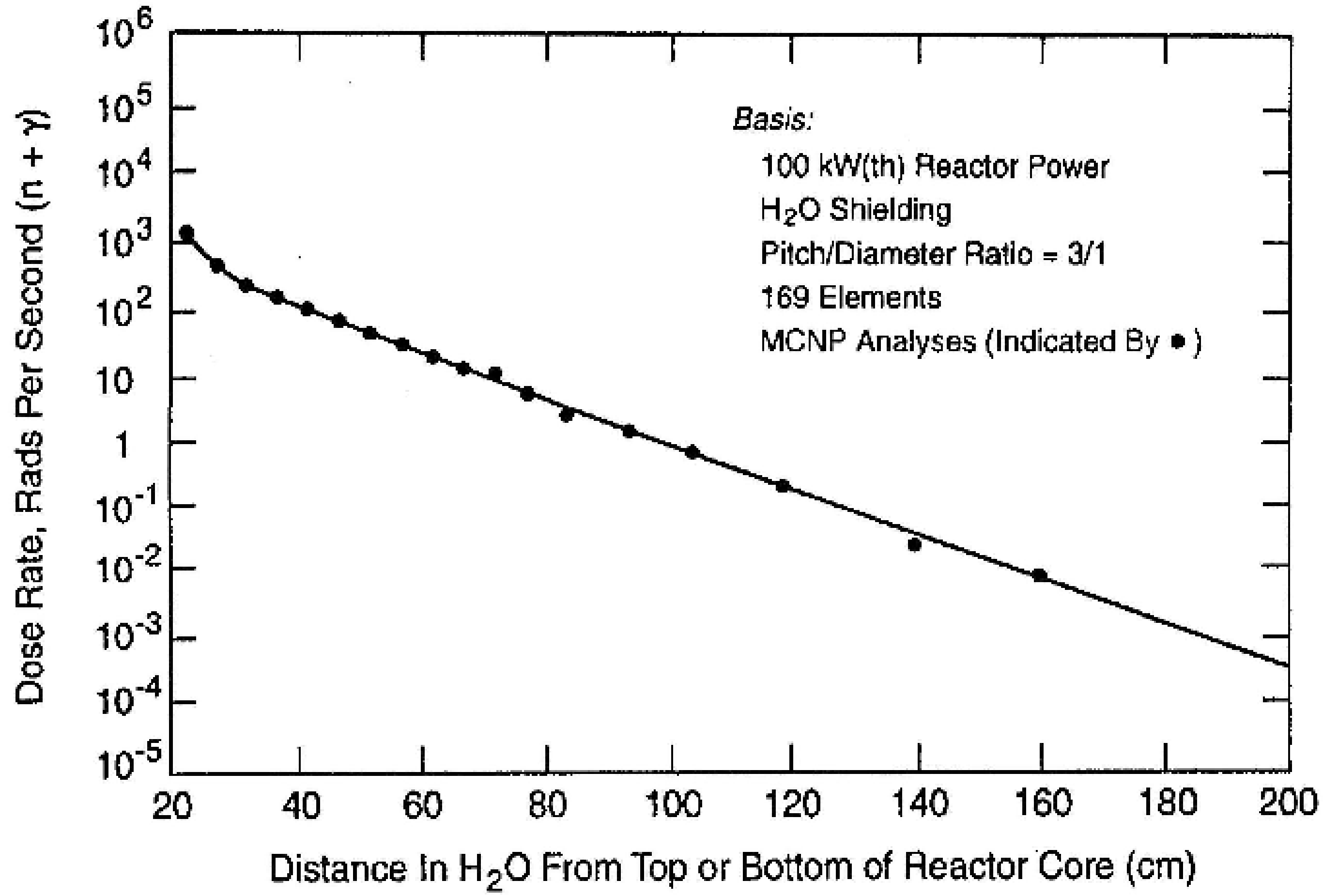


Figure 3.2.7

Flowsheet For MICE Thermal and Electric Power System

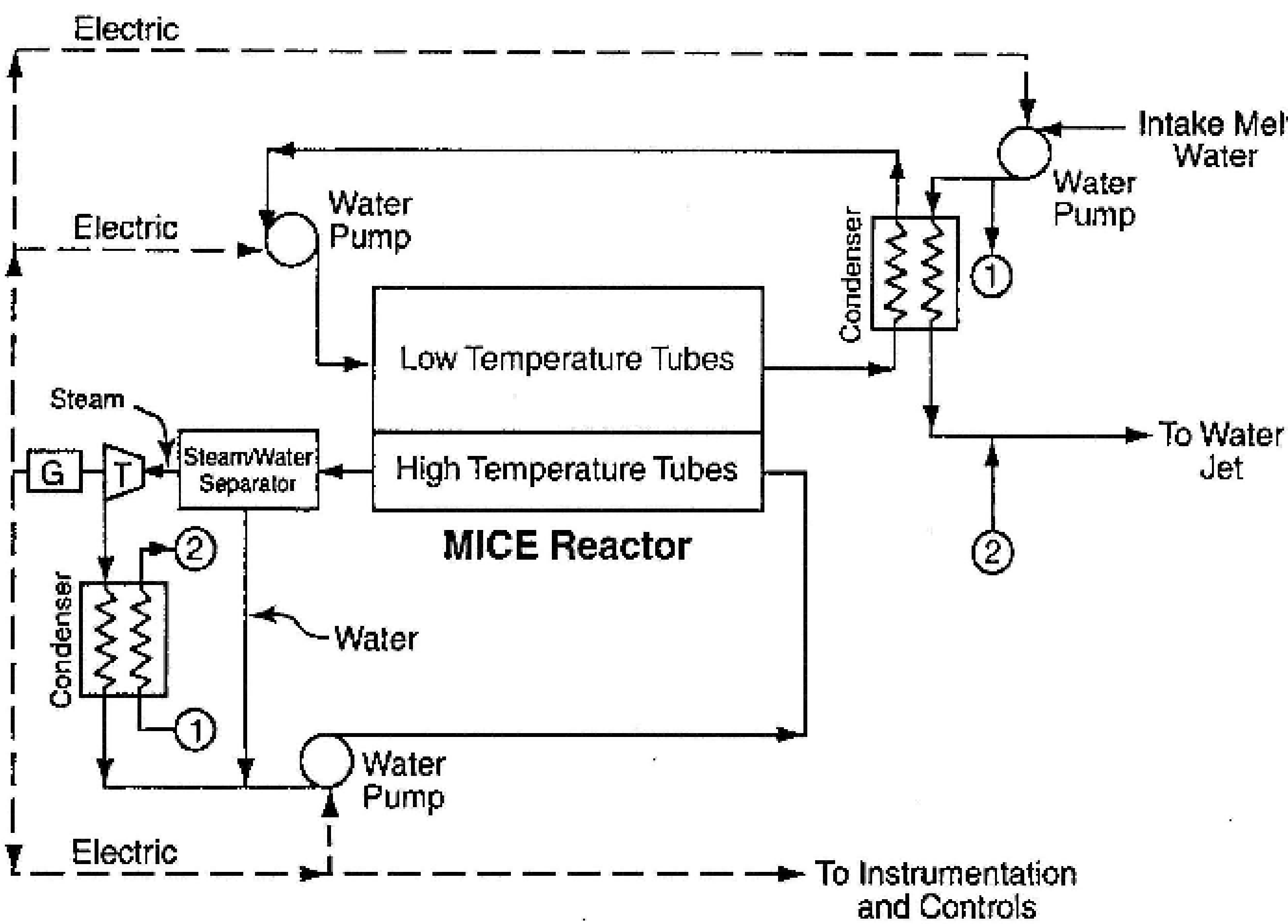


Figure 3.2.8

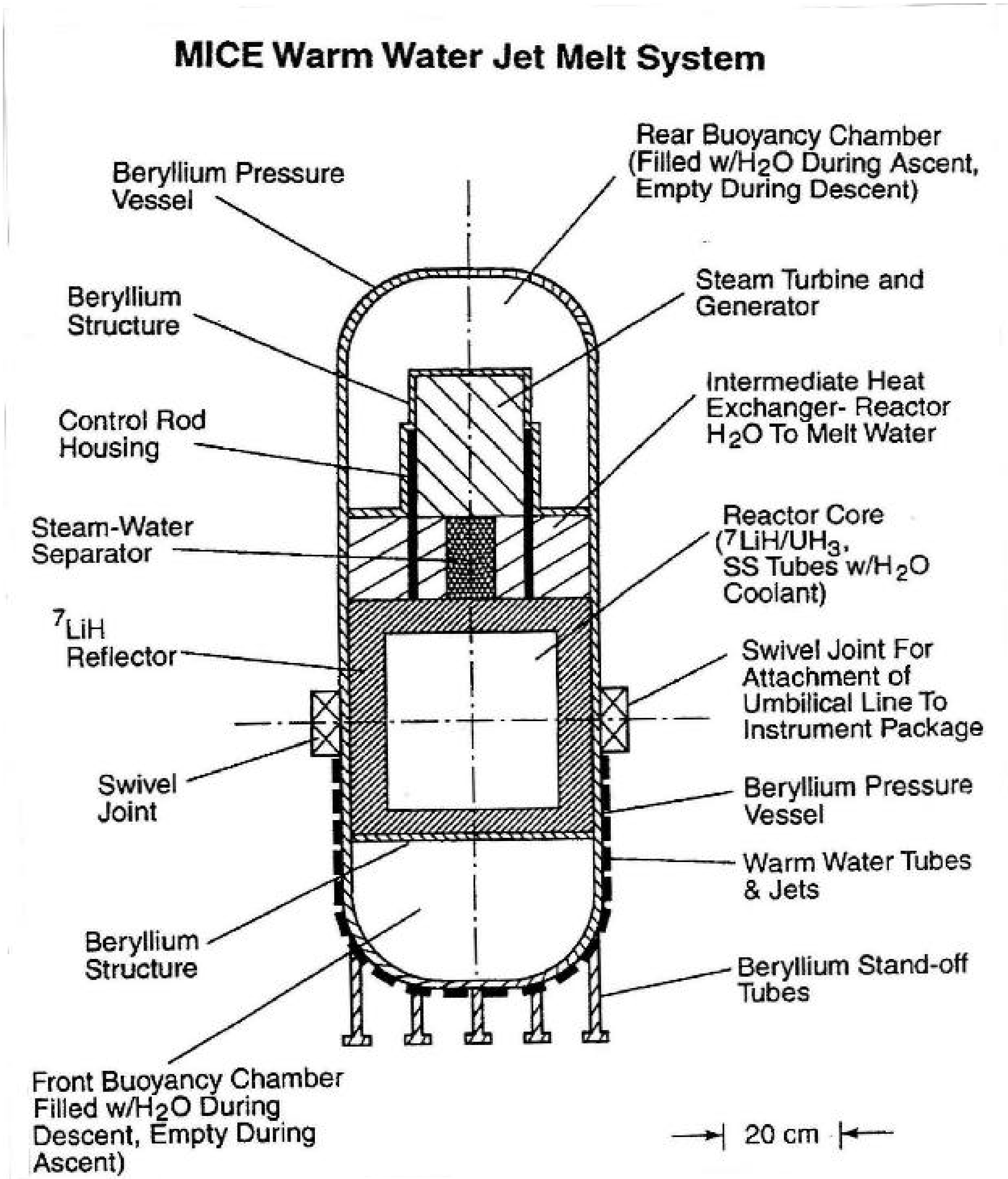

MICE Warm Water Jet Melt System
Beryllium Pressure Vessel
Rear Buoyancy Chamber (Filled w/H2O During Ascent, Empty During Descent)
Beryllium Structure
Steam Turbine and Generator
Control Rod Housing
Intermediate Heat Exchanger- Reactor H2O To Melt Water
Steam-Water Separator
Reactor Core (7LiH/UH3, SS Tubes w/H2O Coolant)
7LiH Reflector
Swivel Joint For Attachment of Umbilical Line To Instrument Package
Swivel Joint
Beryllium Pressure Vessel
Warm Water Tubes & Jets
Beryllium Structure
Beryllium Stand-off Tubes
Front Buoyancy Chamber Filled w/H2O During Descent, Empty During Ascent)
20 cm

Figure 3.2.9

MICE Channel Melt Rate As A Function of Reactor Thermal and Channel Diameter

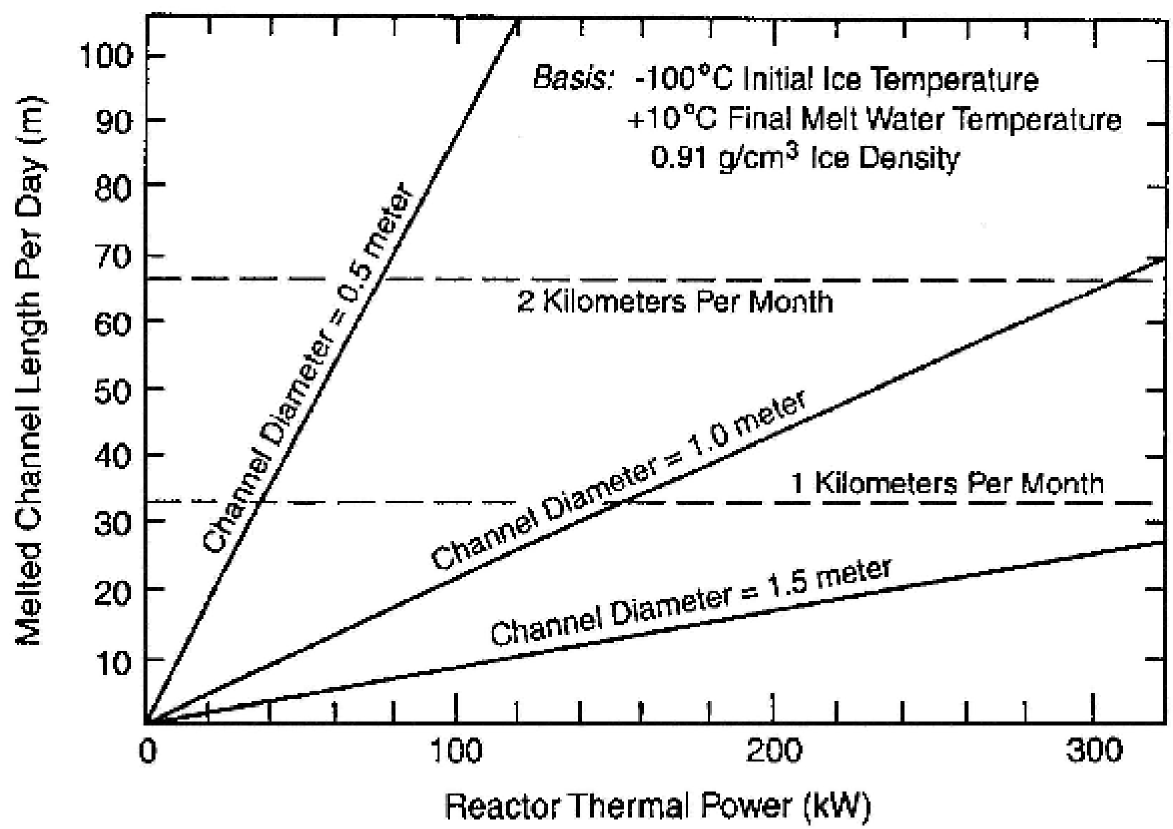


Figure 3.2.10

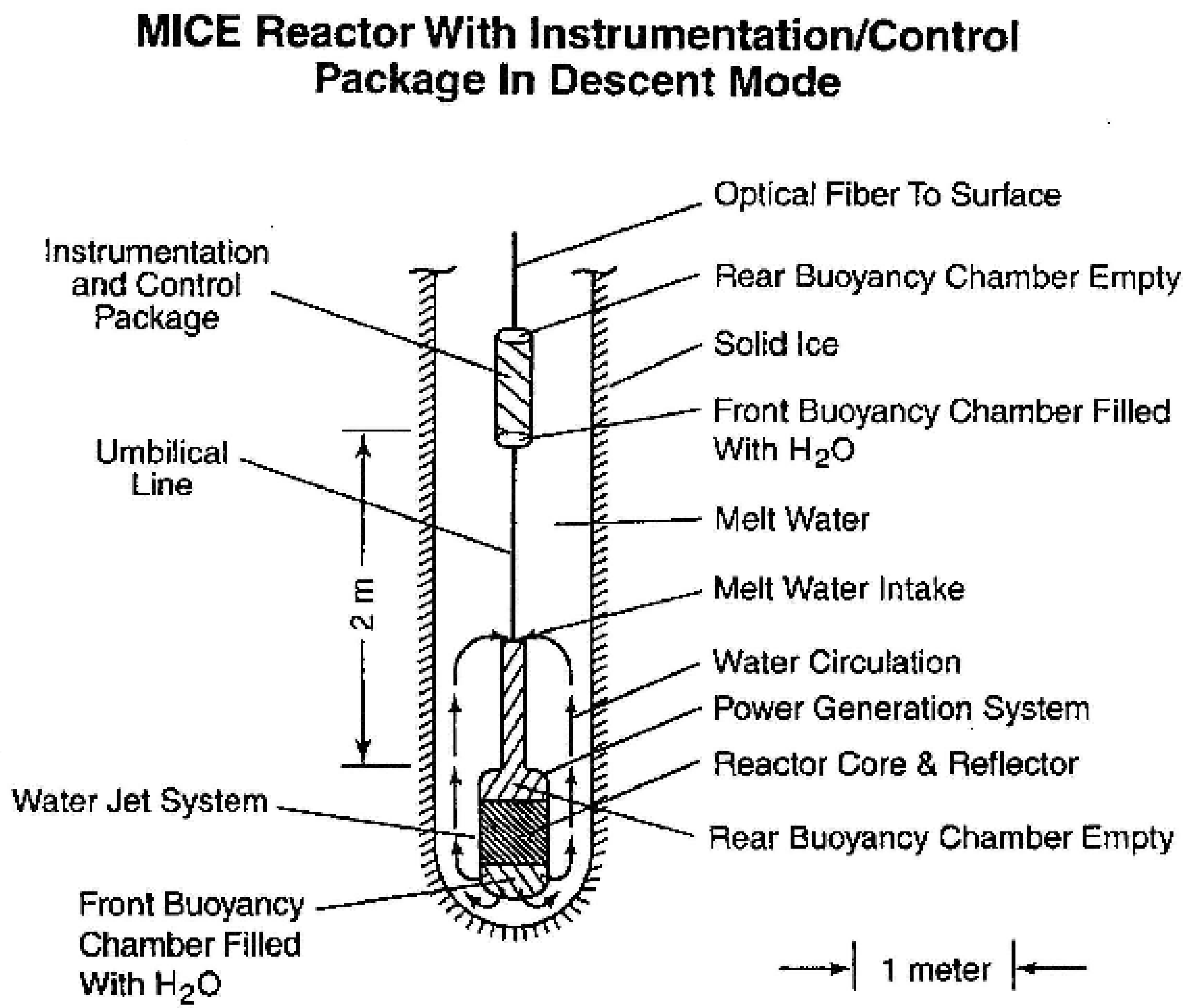

MICE Reactor With Instrumentation/Control
Package In Descent Mode
Optical Fiber To Surface
Rear Buoyancy Chamber Empty
Solid Ice
Front Buoyancy Chamber Filled With H_2O
Melt Water
Melt Water Intake
Water Circulation
Power Generation System
Reactor Core & Reflector
Rear Buoyancy Chamber Empty
Instrumentation and Control Package
Umbilical Line
2 m
Water Jet System
Front Buoyancy Chamber Filled With H_2O
1 meter

Figure 3.2.11

MICE Reactor With Instrumentation/Control Package In Ascent Mode

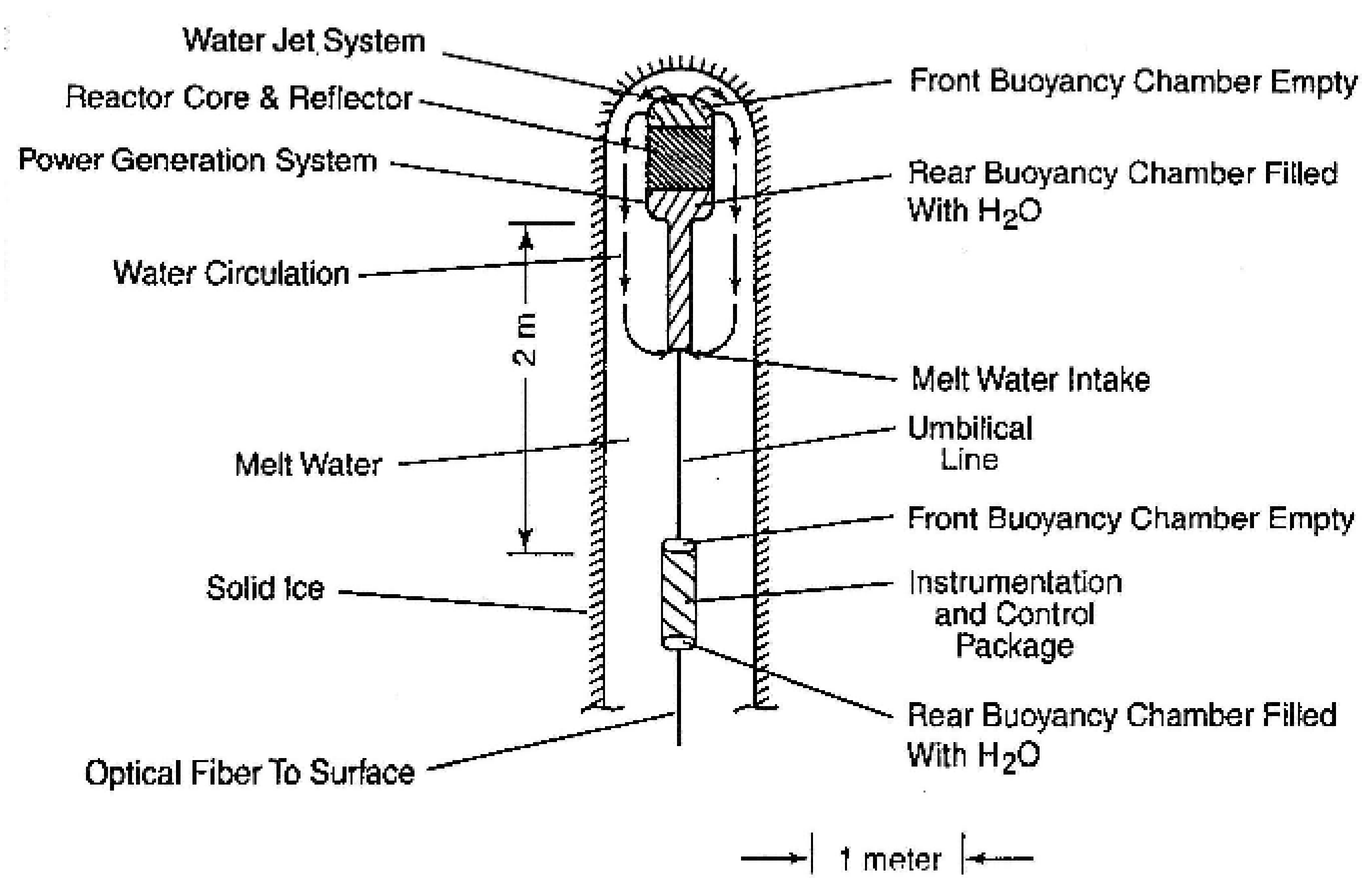


Figure 3.2.12

MICE Data On The Ancient History of Mars

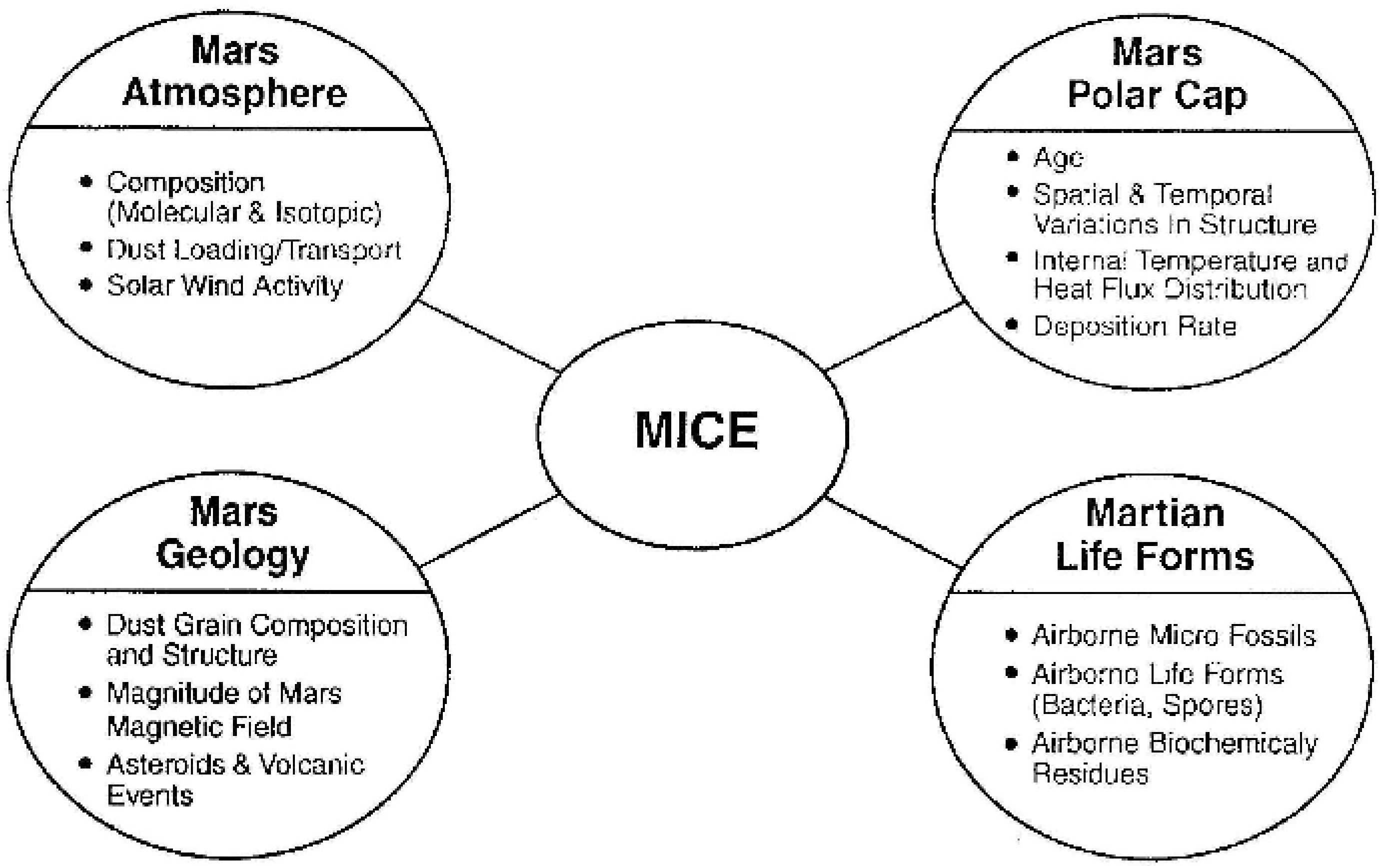


Figure 3.2.13
MICE Mars Mission Architectures

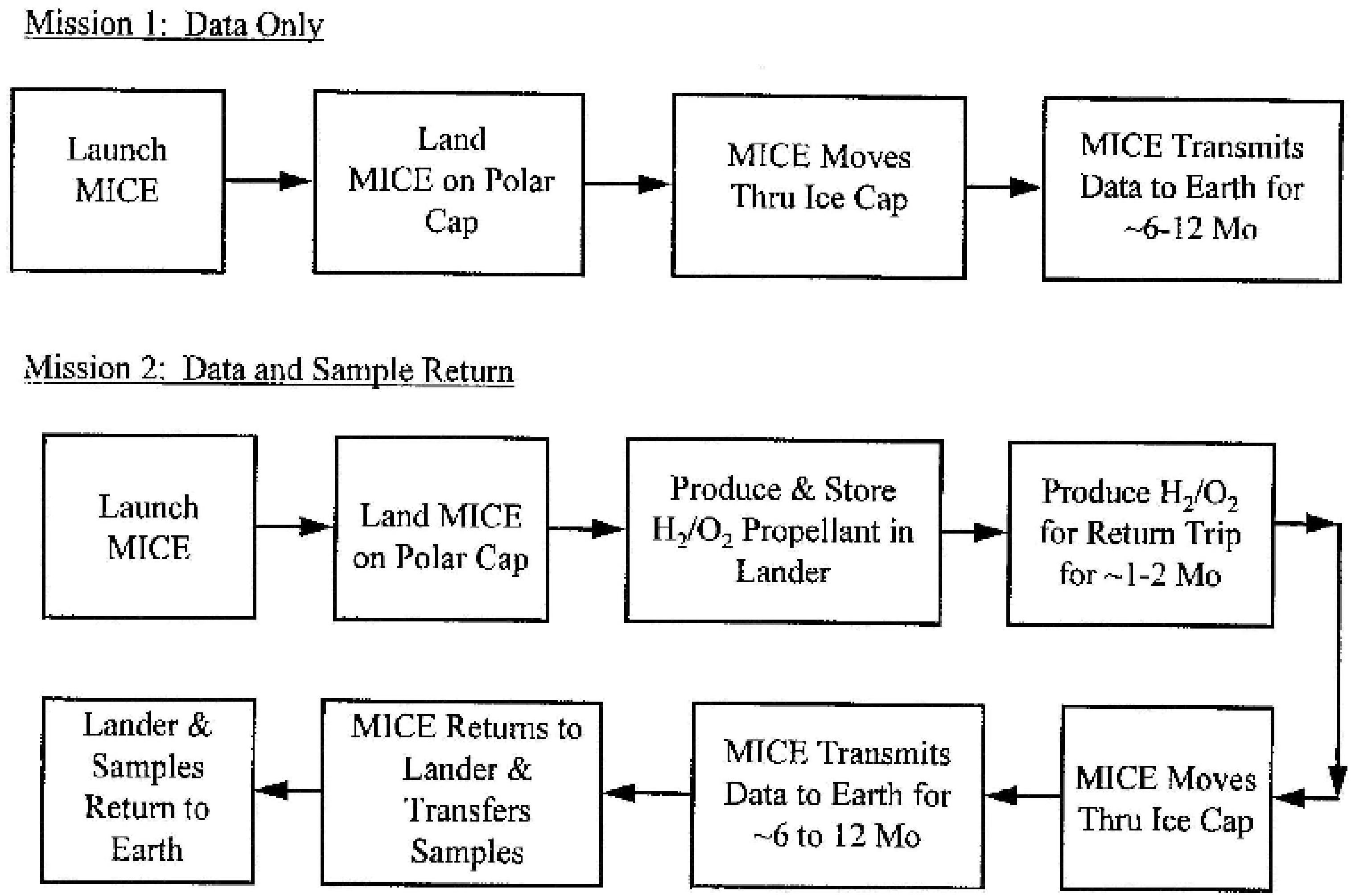


Figure 3.2.14
Illustrative Examples of MICE Measurements and Instruments

<u>Time History of Ancient Martian Atmosphere</u>
- Extract samples of ancient atmosphere as a function of depth (vacuum distillation of melt water)
- Analyze molecular composition (chromatography, spectroscopy, or other)
- Analyze isotopic composition by (AMS or Other)
- Determine dust loading amount and particle size distribution in ancient atmosphere (differential filtration, dust weight fraction in ice)

<u>Time History of Polar Ice Cap</u>
- Rate of consolidation of deposited ice (density vs depth)
- Erosive history (alternating deposition and erosion patterns)
- Age vs depth (^{14}C dating to ~50,000 years; for longer times, use cosmic ray induced spallation products (e.g., ^{26}Al, with 780,000 year half life)
- Mechanical properties vs depth (sound speed, moduli, etc.)
- Temperature and temperature gradient vs depth to provide data on ancient surface temperatures, geothermal heat flow, etc. (micro thermometers on optical fiber link)

<u>Time History of Solar Wind</u>
- Measure ^3He and ^4He contents of ice to determine variations in solar wind activity (AMS, etc.)

<u>Time History of Mars' Geology</u>
- Variations in dust grain composition and structure as a function of time (microscope, spectroscopy, etc.)
- Evidence of ancient anomalous dust events due to volcanoes and asteroid impacts (microscopes, spectroscopy, etc.)

<u>Presence of Martian Life Forms</u>

- Microfossils (microscopes)
- Bacteria (microscopes, nutrient chambers)
- Biochemical residues (PCR, DNA, analysis, etc.)

Figure 3.2.15

MICE as a Precursor to a Manned ALPH Base on Mars

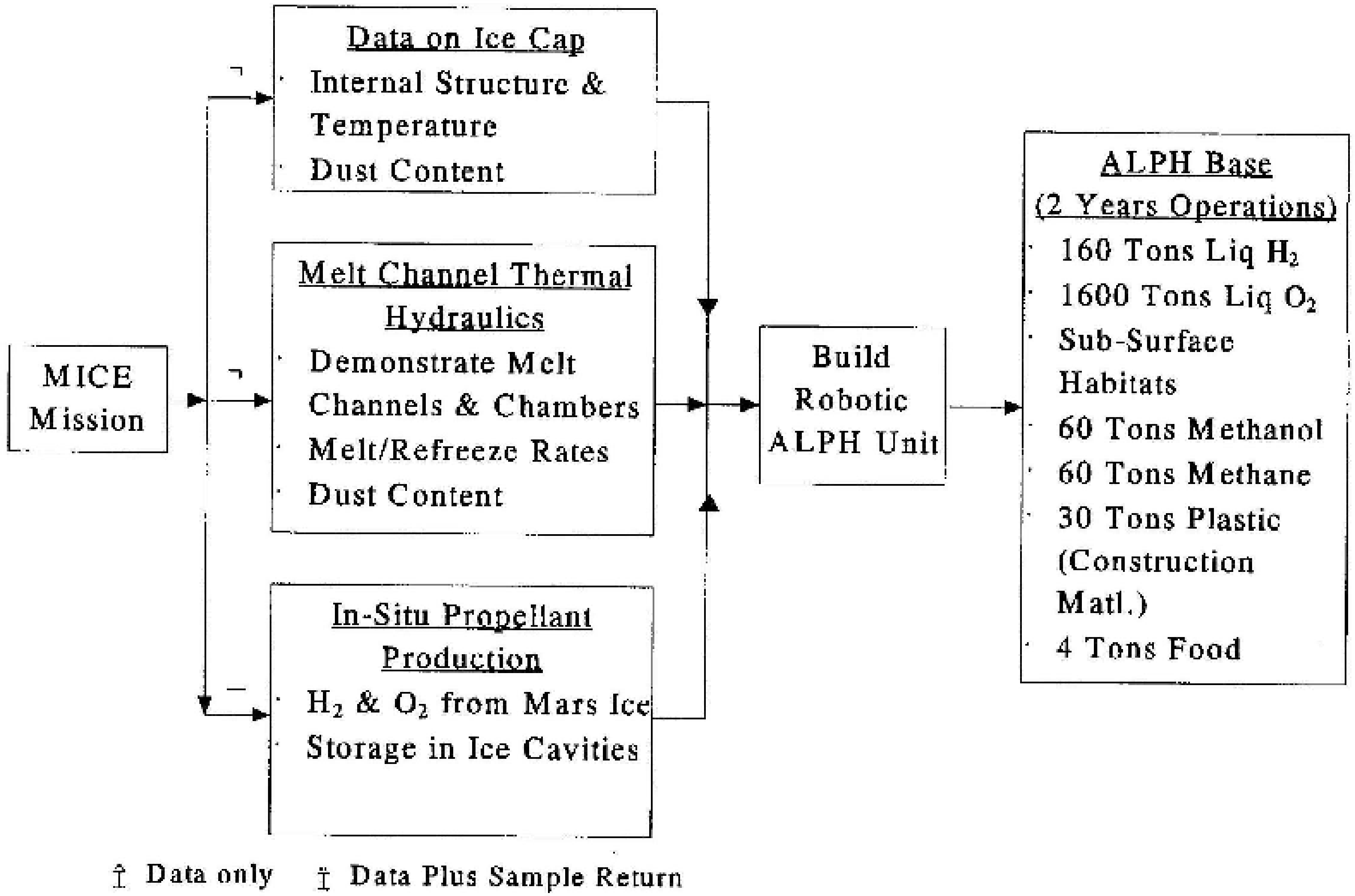


Figure 3.2.16
Road Map for MICE Mission

Phase 1: Component Development (4 years)	Phase 2: System Integration and Field Test (2 years)	Phase 3: Prepare Mission (1 year)
• Electrically Heating MICE Unit in Ice Sheet on Earth	• Integrate MICE Reactor with Melt/Power System & Instruments. Test in Lab	• Obtain Safety Approval
• Construct & Test MICE Reactor and Power System	• Field Test Integrated MICE in Earth Ice Sheet	• Mate MICE Unit to Launch Vehicle
• Develop and Test MICE Instruments	• Finalize MICE Mission Plans	• Final Checkout of MICE and Launch Vehicle
• Define MICE Mission	• Finalize Safety Analyses	
• Preliminary Safety Analyses		

Figure 4.1.1

4.1.1 Principal Features of ALPH

- ALPH Factory Lands at Colony Site on North Polar Cap 20 Months Before Astronauts Leave Earth
- Using Mars Polar Ice and Atmospheric CO_2, ALPH Manufactures Hundreds of Tons of Supplies Including H_2, O_2, and CH_4 Propellants, Methanol Fuel, Breathable Air, Plastics and Food
- Supplies are Stockpiled and In-Place in Sub-Surface Ice Cavities, Ready for Use, Before Astronauts Leave Earth
- ALPH has Compact, Lightweight Reactor, Steam Turbo-Generator, and Process Units, Based on Existing Technology
- ALPH also Creates Large Sub-Surface Habitats for Astronauts to Fully Shield Them from Cosmic Rays

Figure 4.1.2

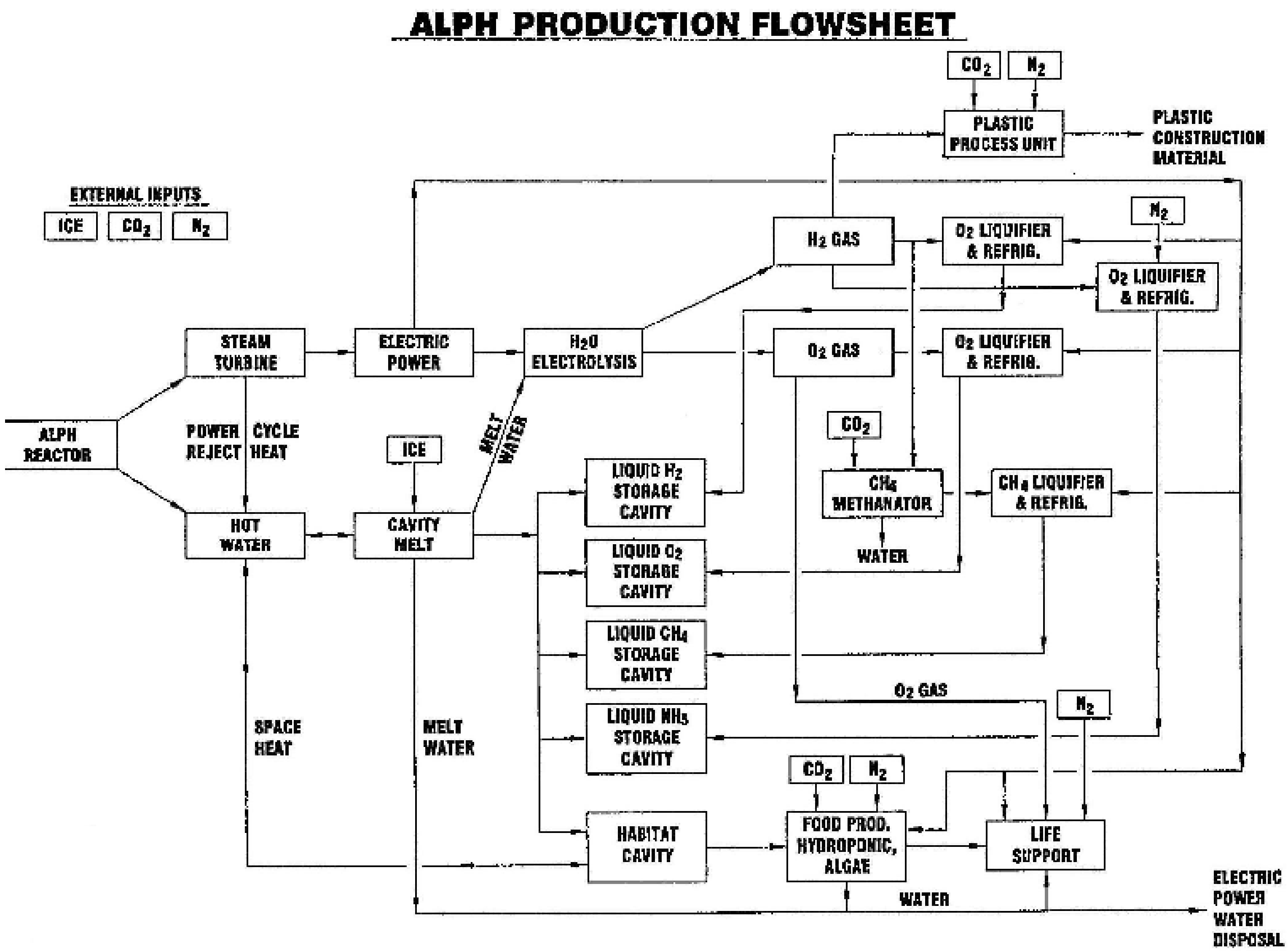

ALPH PRODUCTION FLOWSHEET
EXTERNAL INPUTS
ICE
CO_2
N_2
ALPH REACTOR
STEAM TURBINE
POWER CYCLE REJECT HEAT
HOT WATER
ELECTRIC POWER
ICE
CAVITY MELT
MELT WATER
H_2O ELECTROLYSIS
H_2 GAS
O_2 GAS
CO_2
N_2
PLASTIC PROCESS UNIT
PLASTIC CONSTRUCTION MATERIAL
O_2 LIQUIFIER & REFRIG.
N_2
O_2 LIQUIFIER & REFRIG.
O_2 LIQUIFIER & REFRIG.
CO_2
CH_4 METHANATOR
WATER
CH_4 LIQUIFIER & REFRIG.
LIQUID H_2 STORAGE CAVITY
LIQUID O_2 STORAGE CAVITY
LIQUID CH_4 STORAGE CAVITY
LIQUID NH_3 STORAGE CAVITY
O_2 GAS
N_2
HABITAT CAVITY
CO_2
N_2
FOOD PROD. HYDROPONIC, ALGAE
LIFE SUPPORT
SPACE HEAT
MELT WATER
WATER
ELECTRIC POWER WATER DISPOSAL

Figure 4.2.1

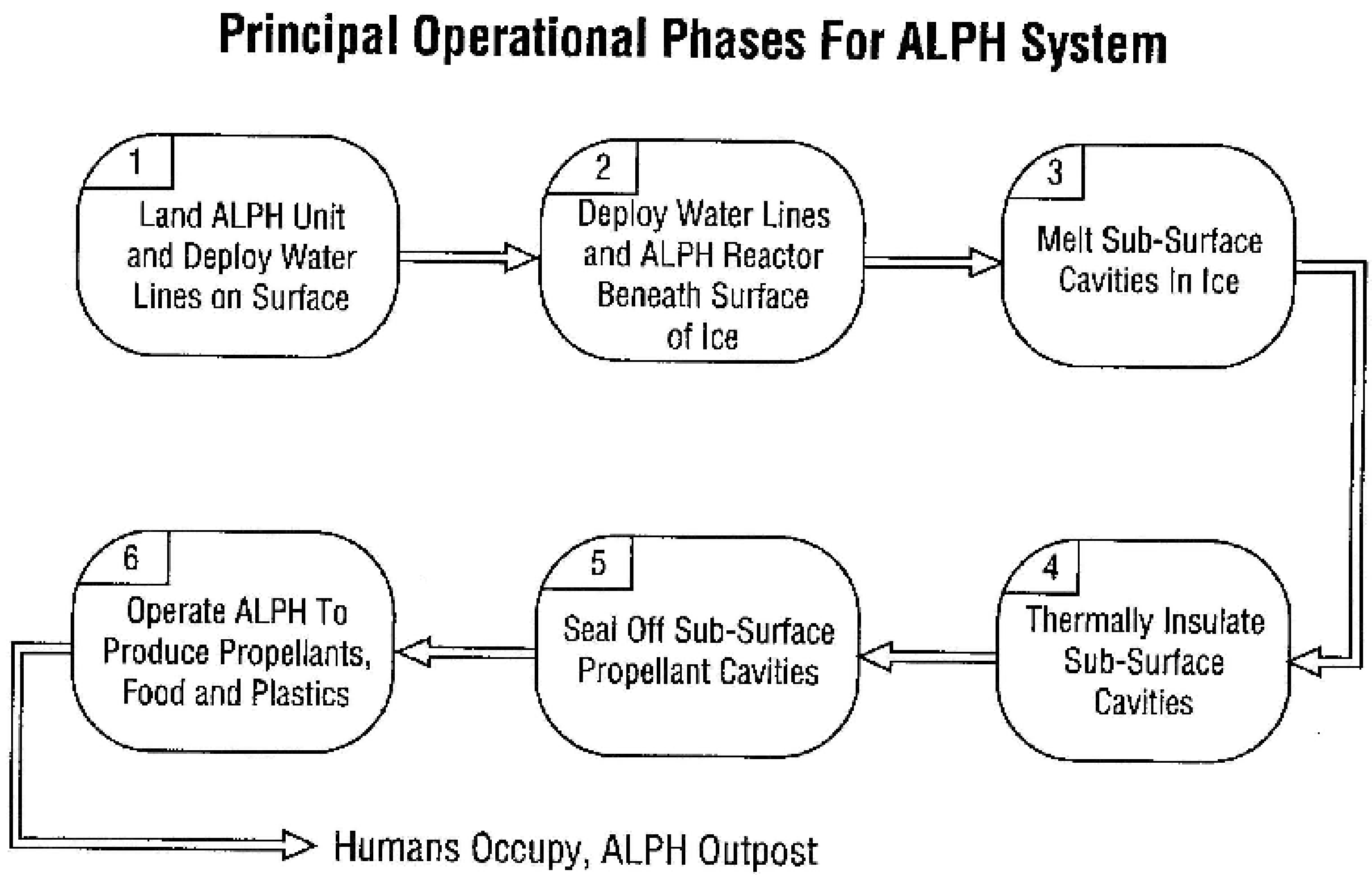

Principal Operational Phases For ALPH System
1
Land ALPH Unit and Deploy Water Lines on Surface
2
Deploy Water Lines and ALPH Reactor Beneath Surface of Ice
3
Melt Sub-Surface Cavities In Ice
4
Thermally Insulate Sub-Surface Cavities
5
Seal Off Sub-Surface Propellant Cavities
6
Operate ALPH To Produce Propellants, Food and Plastics
Humans Occupy, ALPH Outpost

Figure 4.2.2

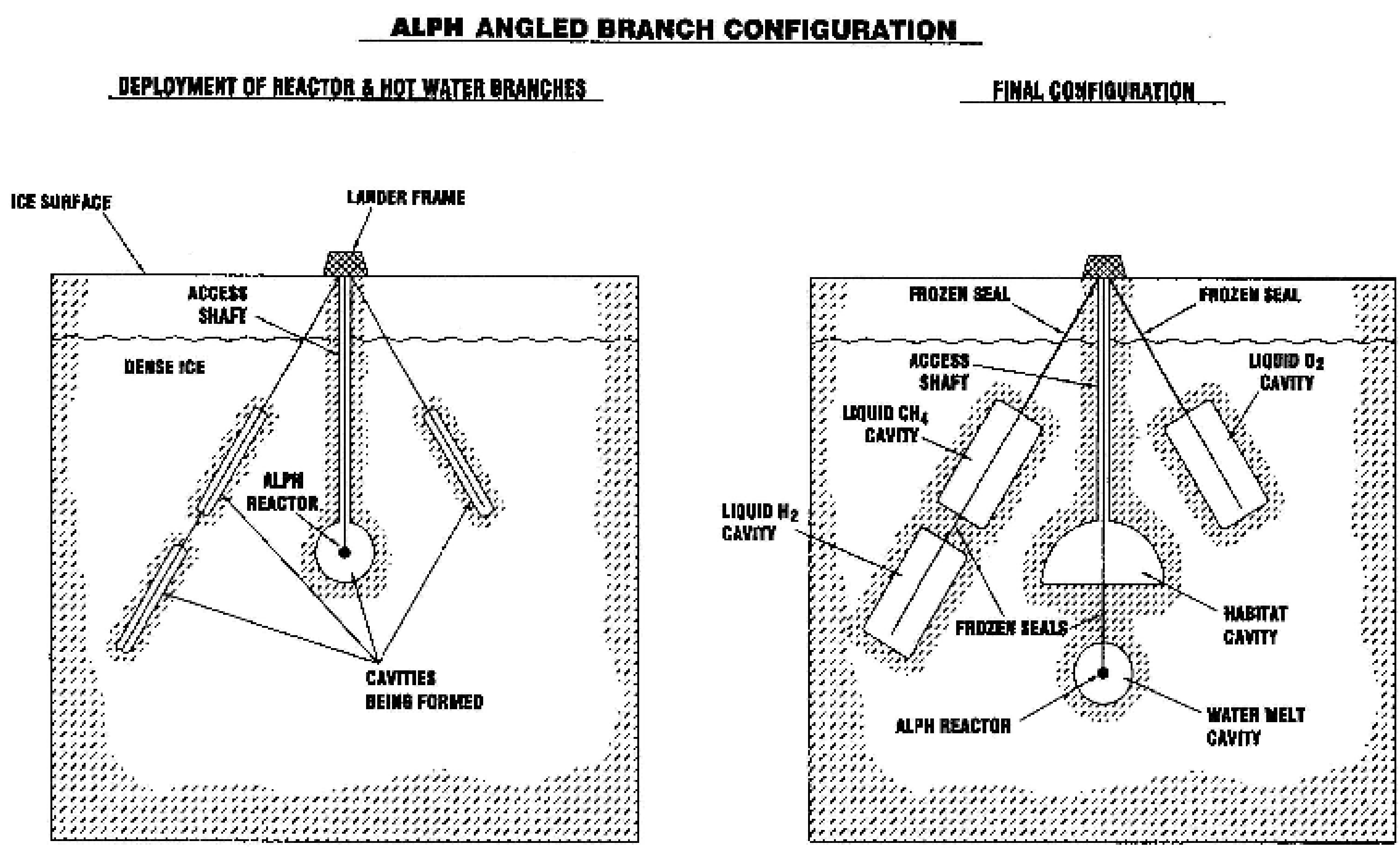

ALPH ANGLED BRANCH CONFIGURATION
DEPLOYMENT OF REACTOR & HOT WATER BRANCHES
ICE SURFACE
LANDER FRAME
ACCESS SHAFT
DENSE ICE
ALPH REACTOR
CAVITIES BEING FORMED
FINAL CONFIGURATION
FROZEN SEAL
FROZEN SEAL
ACCESS SHAFT
LIQUID O_2 CAVITY
LIQUID CH_4 CAVITY
LIQUID H_2 CAVITY
FROZEN SEALS
HABITAT CAVITY
ALPH REACTOR
WATER MELT CAVITY

Figure 4.2.3

TOP VIEW OF ANGLED BRANCH CONFIGURATION

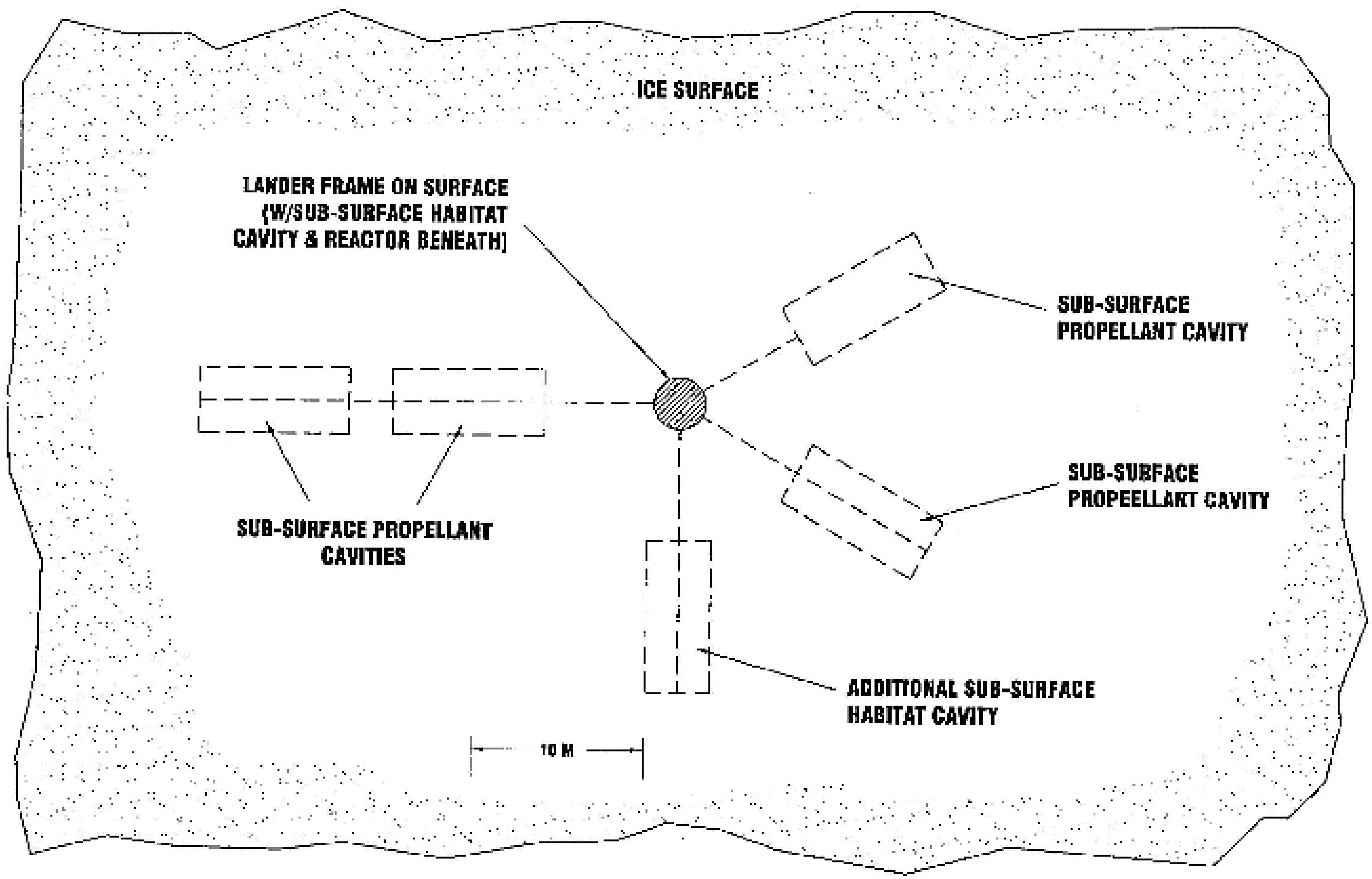


Figure 4.2.4

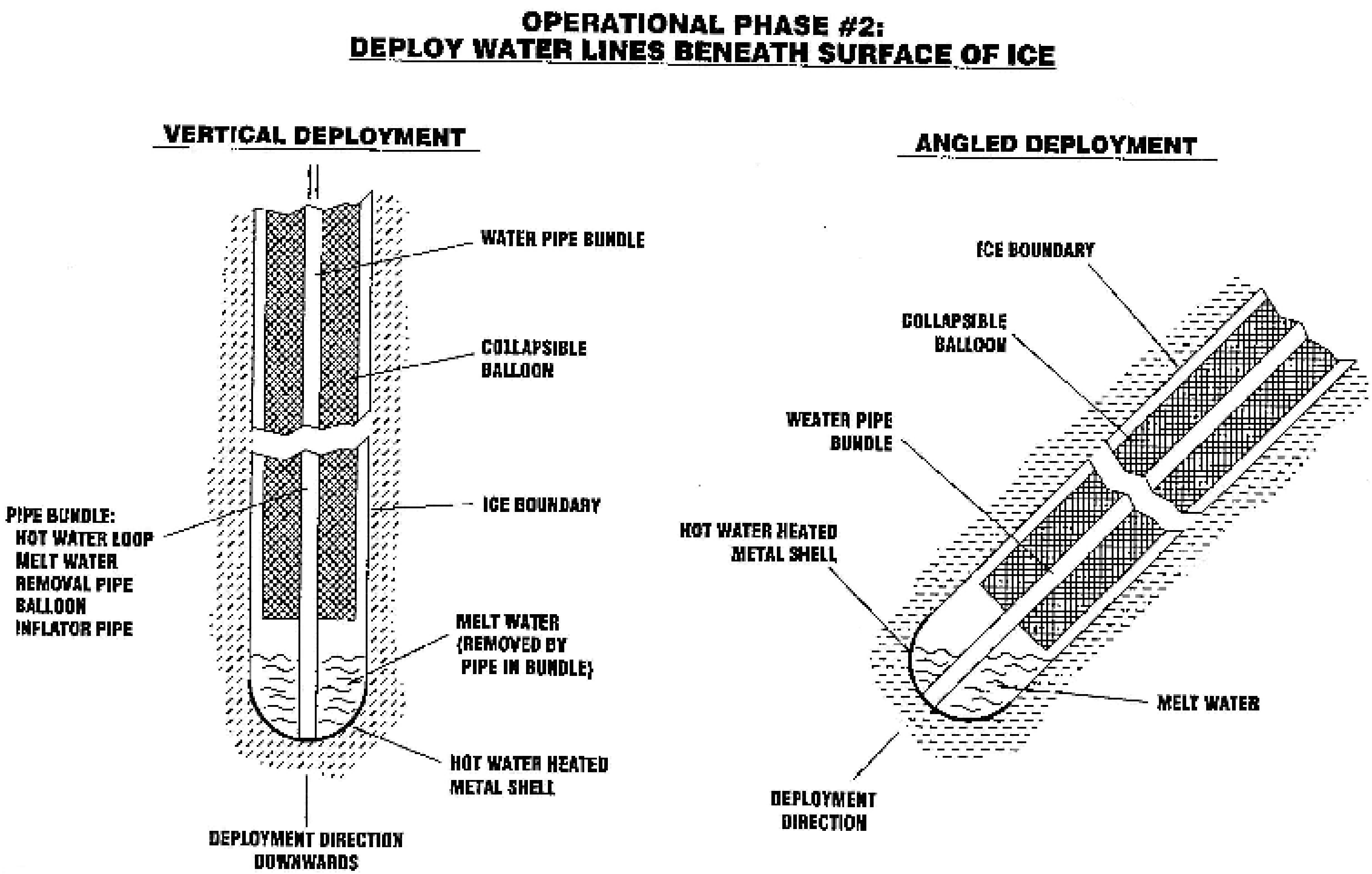

OPERATIONAL PHASE #2:
DEPLOY WATER LINES BENEATH SURFACE OF ICE
VERTICAL DEPLOYMENT
WATER PIPE BUNDLE
COLLAPSIBLE BALLOON
ICE BOUNDARY
PIPE BUNDLE: HOT WATER LOOP MELT WATER REMOVAL PIPE BALLOON INFLATOR PIPE
MELT WATER (REMOVED BY PIPE IN BUNDLE)
HOT WATER HEATED METAL SHELL
DEPLOYMENT DIRECTION DOWNWARDS
ANGLED DEPLOYMENT
ICE BOUNDARY
COLLAPSIBLE BALLOON
WEATER PIPE BUNDLE
HOT WATER HEATED METAL SHELL
MELT WATER
DEPLOYMENT DIRECTION

Figure 4.2.5

Melt Rate For Sub-Surface ALPH Cylindrical Cavities In Ice

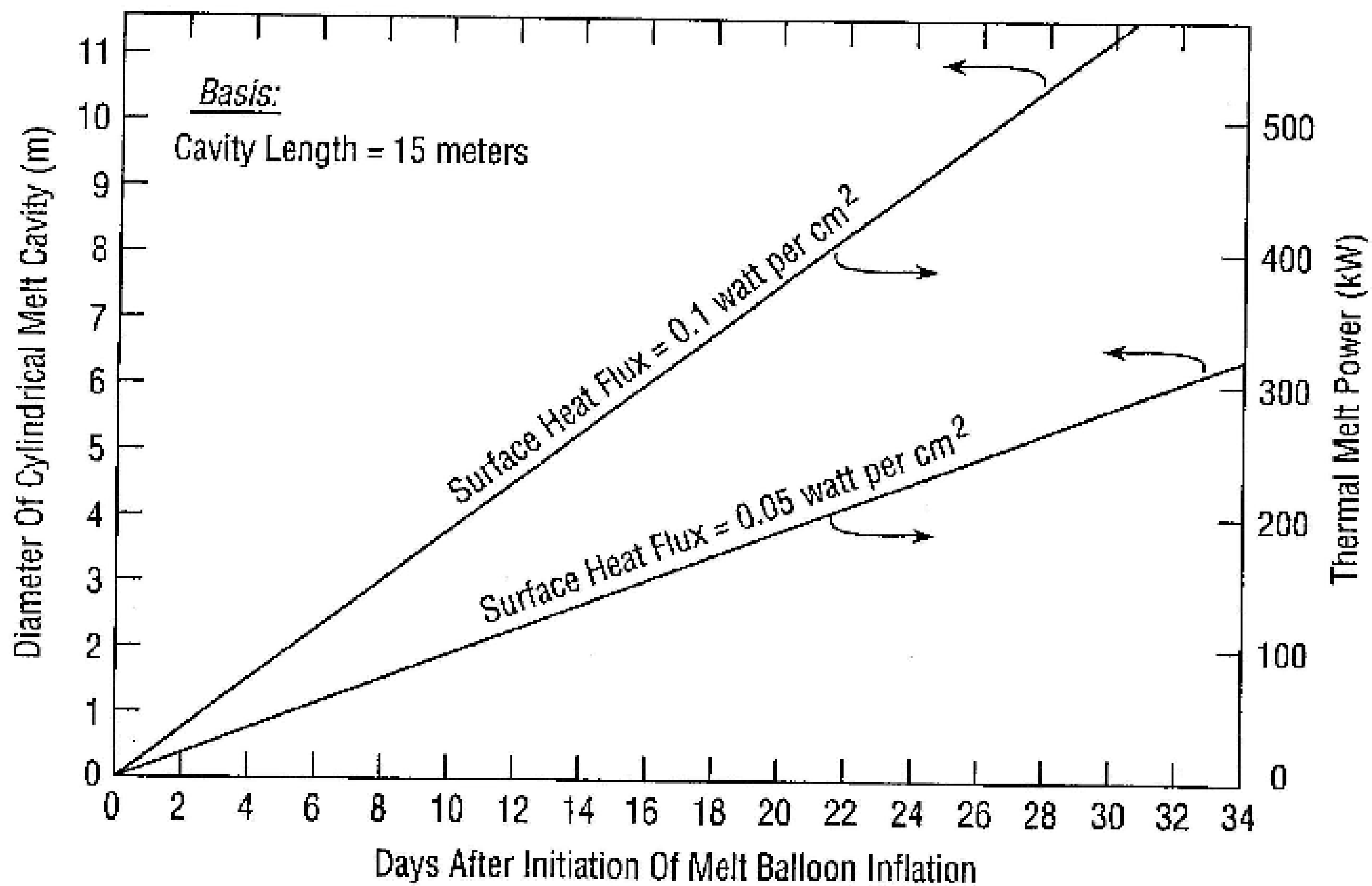


Figure 4.2.6

Figure 4.2.7

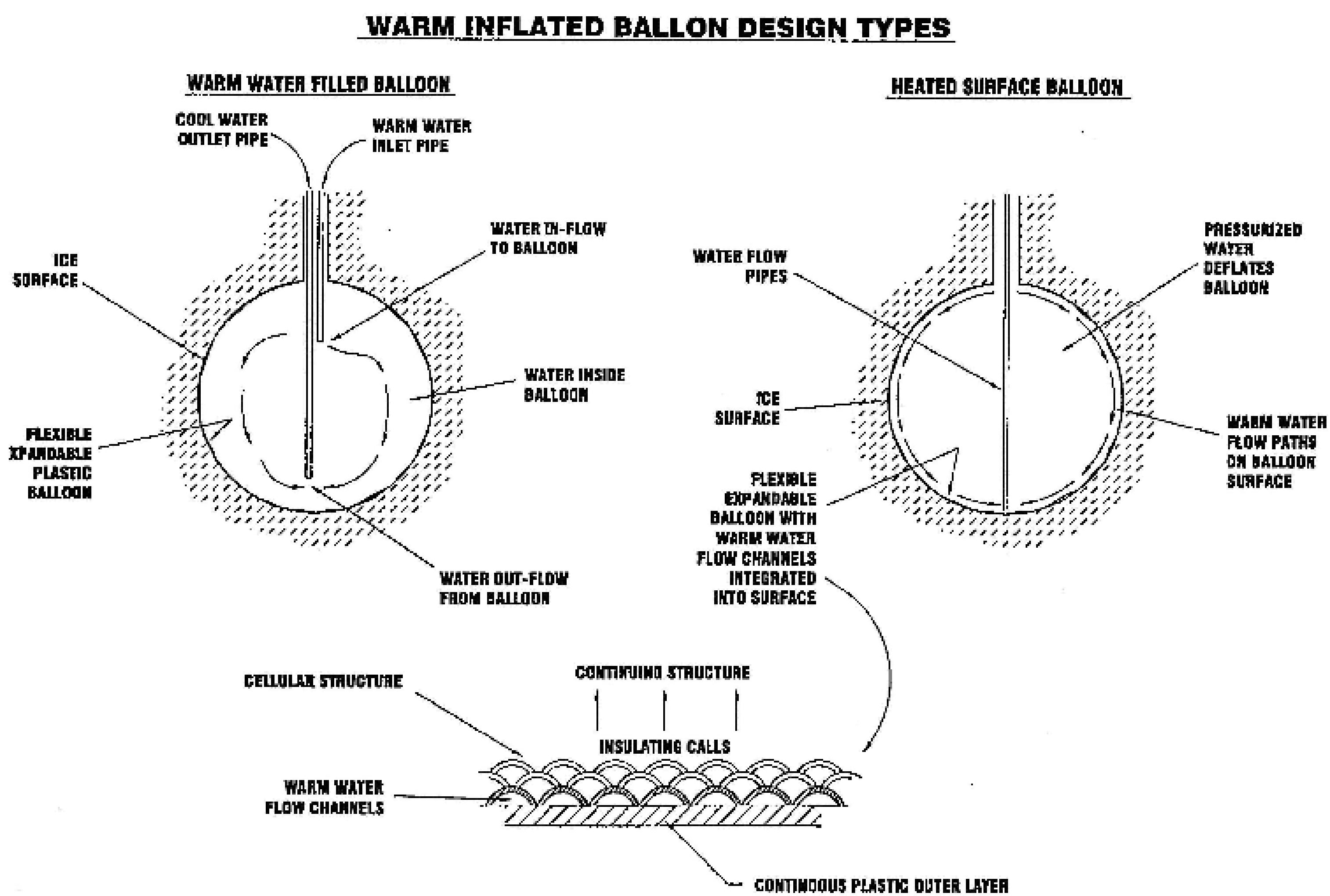
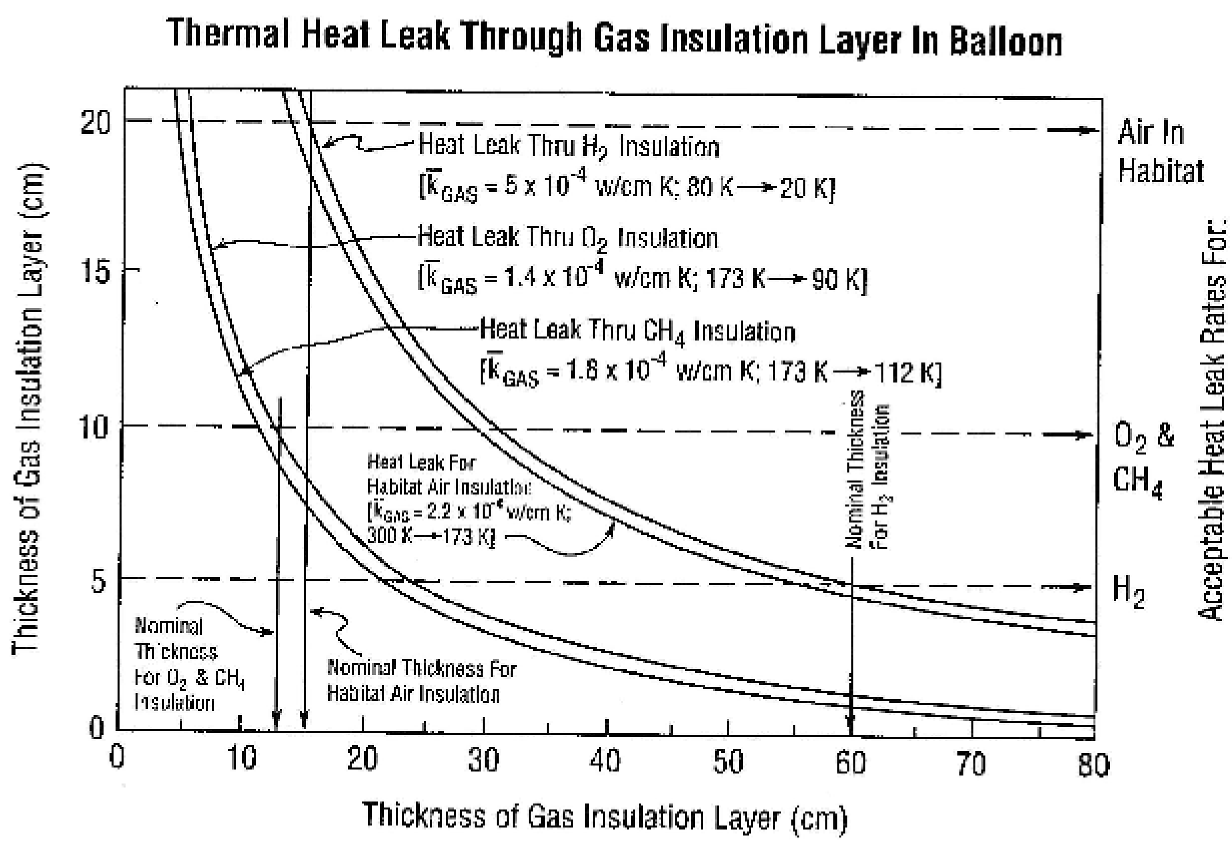

WARM INFLATED BALLON DESIGN TYPES
WARM WATER FILLED BALLOON
COOL WATER OUTLET PIPE
WARM WATER INLET PIPE
WATER IN-FLOW TO BALLOON
ICE SURFACE
WATER INSIDE BALLOON
FLEXIBLE XPANDABLE PLASTIC BALLOON
WATER OUT-FLOW FROM BALLOON
HEATED SURFACE BALLOON
WATER FLOW PIPES
PRESSURIZED WATER DEFLATES BALLOON
ICE SURFACE
WARM WATER FLOW PATHS ON BALLOON SURFACE
FLEXIBLE EXPANDABLE BALLOON WITH WARM WATER FLOW CHANNELS INTEGRATED INTO SURFACE
CELLULAR STRUCTURE
CONTINUING STRUCTURE
INSULATING CALLS
WARM WATER FLOW CHANNELS
CONTINOOUS PLASTIC OUTER LAYER

Figure 4.2.8



Thermal Heat Leak Through Gas Insulation Layer In Balloon
Heat Leak Thru H2 Insulation
[k̄GAS = 5 x 10-4 w/cm K; 80 K → 20 K]
Heat Leak Thru O2 Insulation
[k̄GAS = 1.4 x 10-4 w/cm K; 173 K → 90 K]
Heat Leak Thru CH4 Insulation
[k̄GAS = 1.8 x 10-4 w/cm K; 173 K → 112 K]
Heat Leak For Habitat Air Insulation [k̄GAS = 2.2 x 10-4 w/cm K; 300 K → 173 K]
Nominal Thickness For O2 & CH4 Insulation
Nominal Thickness For Habitat Air Insulation
Nominal Thickness For H2 Insulation
Air In Habitat
O2 & CH4
H2
Acceptable Heat Leak Rates For:
Thickness of Gas Insulation Layer (cm)
Thickness of Gas Insulation Layer (cm)
0
5
10
15
20
0
10
20
30
40
50
60
70
80

Figure 4.2.9

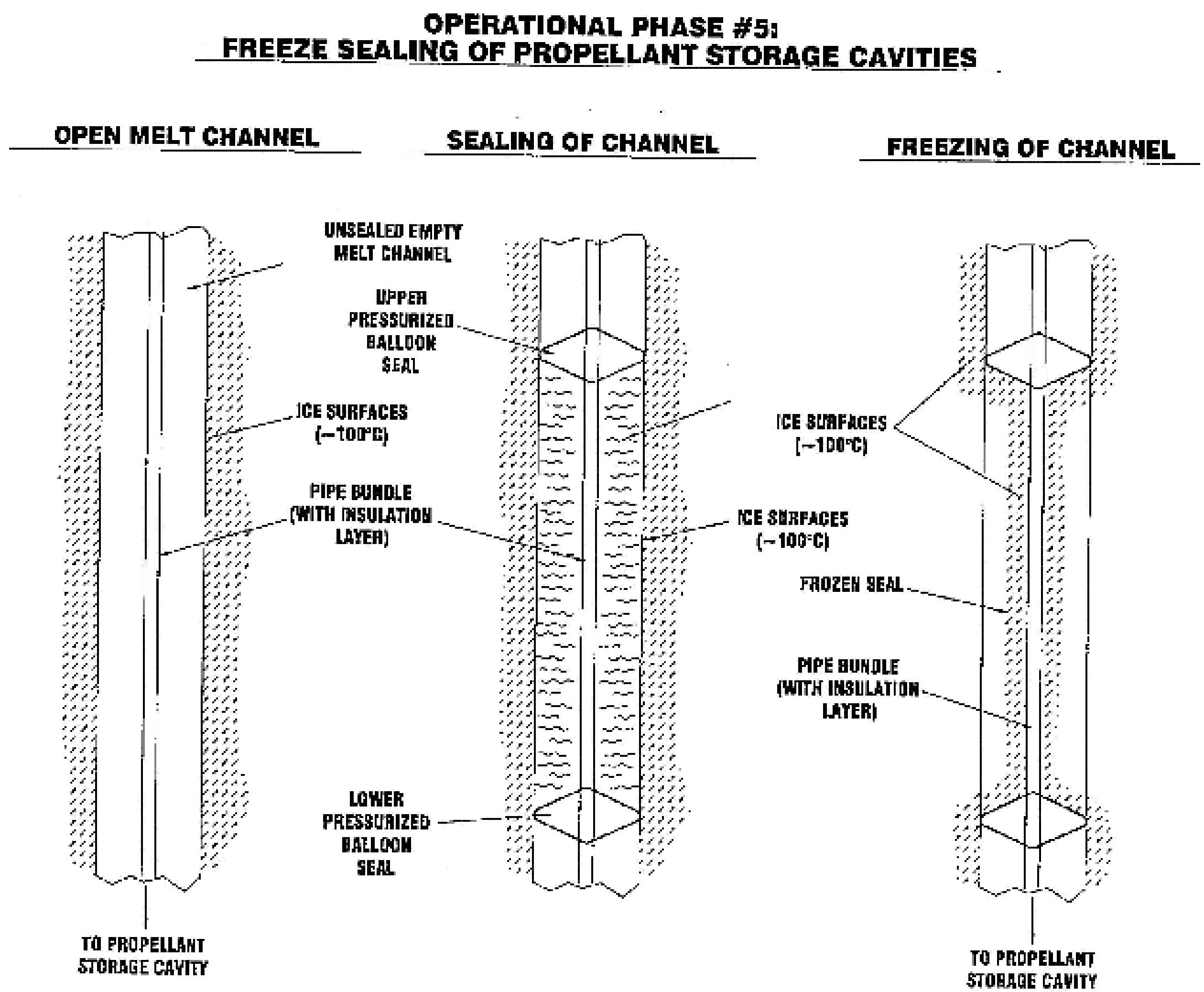

OPERATIONAL PHASE #5:
FREEZE SEALING OF PROPELLANT STORAGE CAVITIES
OPEN MELT CHANNEL
SEALING OF CHANNEL
FREEZING OF CHANNEL
UNSEALED EMPTY MELT CHANNEL
UPPER PRESSURIZED BALLOON SEAL
ICE SURFACES (~100°C)
PIPE BUNDLE (WITH INSULATION LAYER)
LOWER PRESSURIZED BALLOON SEAL
ICE SURFACES (~100°C)
ICE SURFACES (~100°C)
FROZEN SEAL
PIPE BUNDLE (WITH INSULATION LAYER)
TO PROPELLANT STORAGE CAVITY
TO PROPELLANT STORAGE CAVITY

Figure 4.3.1

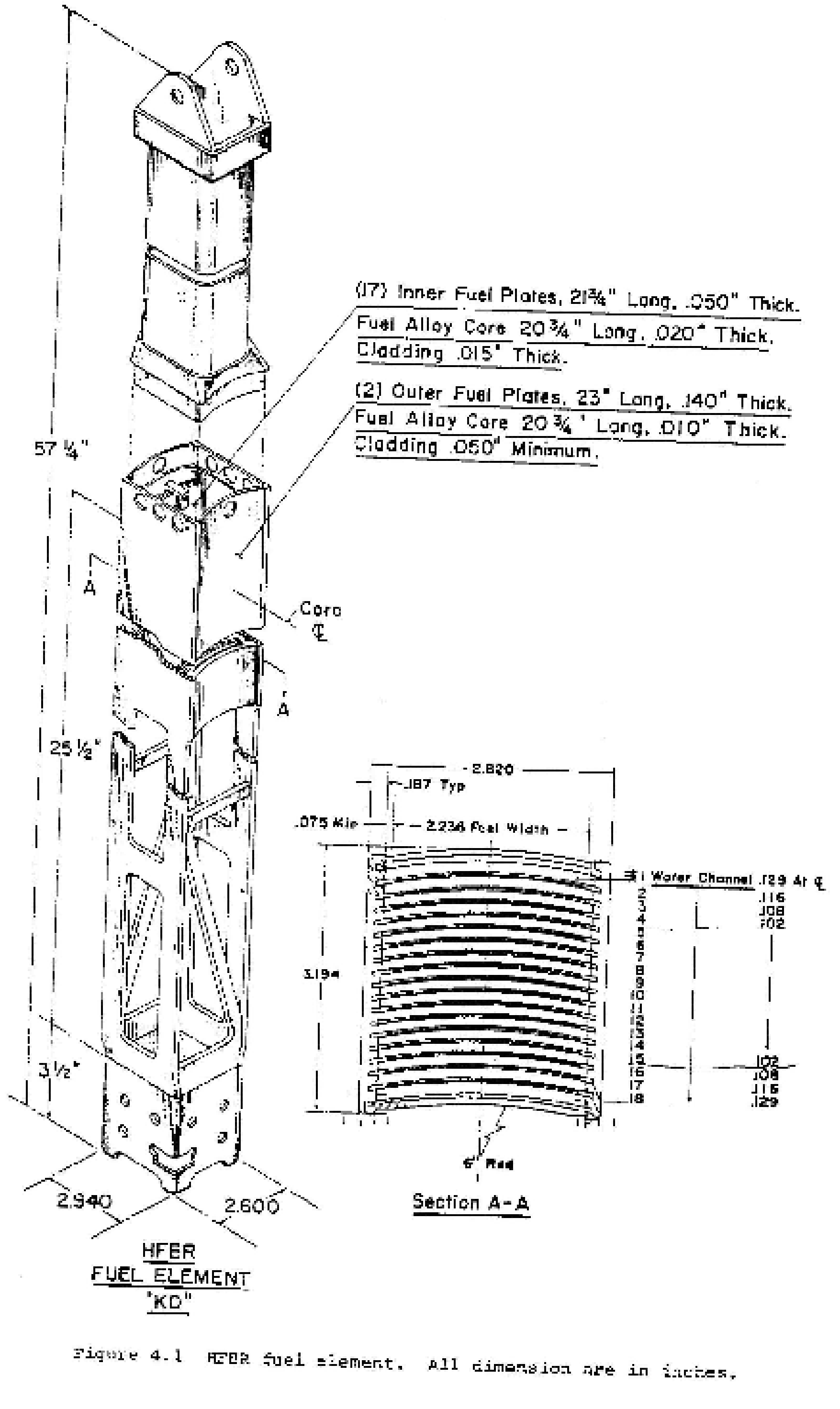


Figure 4.1 HFBR fuel element. All dimension are in inches.

Figure 4.3.2

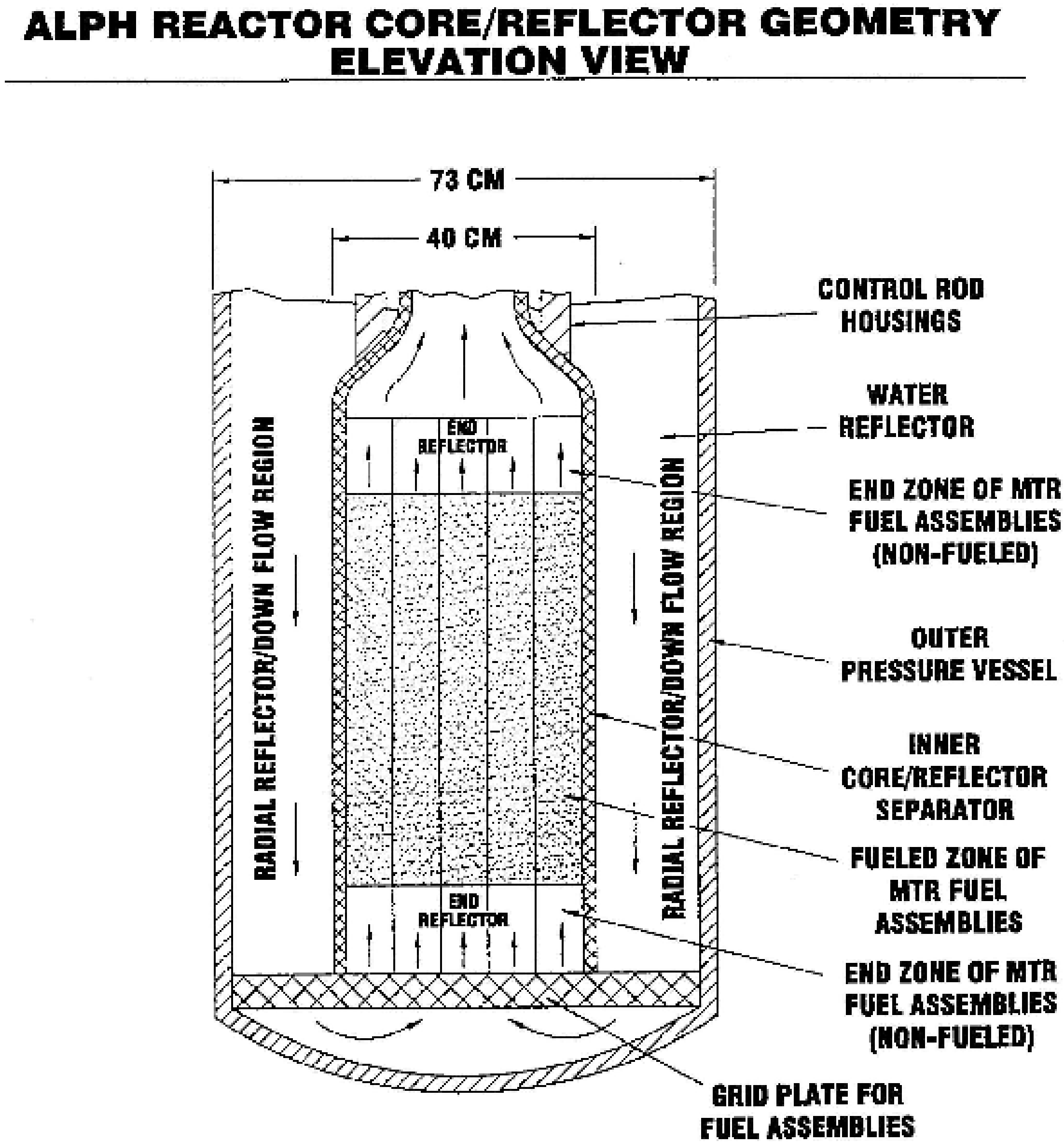

ALPH REACTOR CORE/REFLECTOR GEOMETRY
ELEVATION VIEW
73 CM
40 CM
CONTROL ROD HOUSINGS
WATER REFLECTOR
END REFLECTOR
END ZONE OF MTR FUEL ASSEMBLIES (NON-FUELED)
OUTER PRESSURE VESSEL
INNER CORE/REFLECTOR SEPARATOR
FUELED ZONE OF MTR FUEL ASSEMBLIES
END REFLECTOR
END ZONE OF MTR FUEL ASSEMBLIES (NON-FUELED)
GRID PLATE FOR FUEL ASSEMBLIES
RADIAL REFLECTOR/DOWN FLOW REGION
RADIAL REFLECTOR/DOWN FLOW REGION

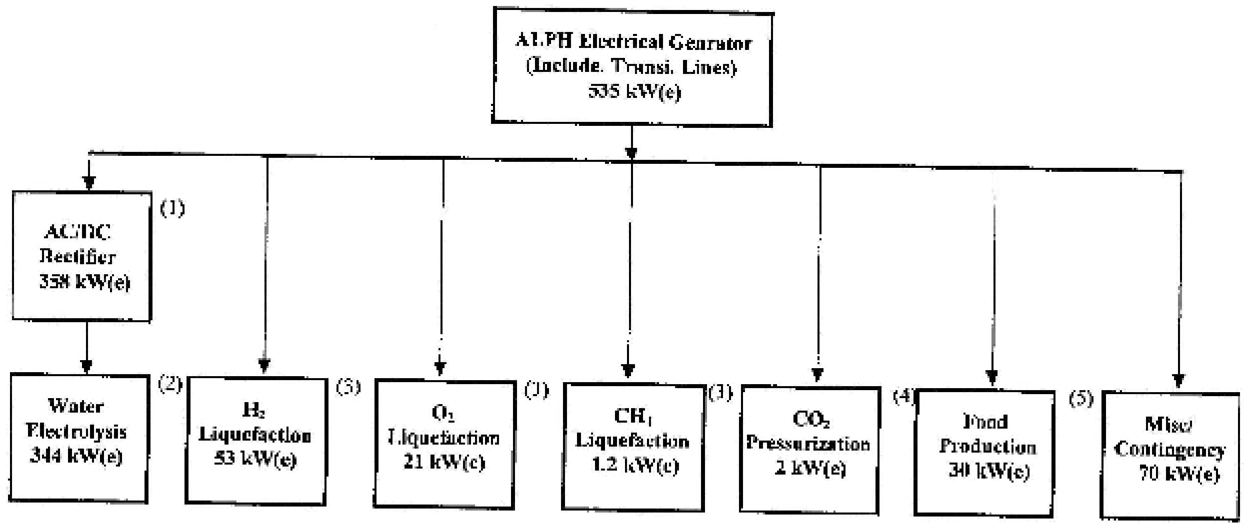
Figure 4.3.3

Figure 4.3.' ALPH Reactor Based on MICE Technology

- Greater Thermal Power Than MICE (2.7 MW(th) compared to 0.2 MW(th)
- Greater Diameter Than MICE (35 centimeters compared to 29 centimeters for MICE)
- Higher Outlet Temperature for H_2O Coolant (270° C vs 50° C for most of MICE coolant tubes)
- Higher Coolant Velocity (5 m/sec vs 1 m/sec for MICE)
- Greater ΔT Across Core (30° C vs 20° C for MICE)

Figure 4.3.4

Electric Energy Distribution Flowsheet During Phase I Operation
(Basis: 1 ALPH Unit)



1) AC/DC rectifier efficiency = 96%
2) 1.6 volts for H_2 production (reversible voltage = 1.23 V; thermoneutral voltage = 1.48 V)
3) Heat sink at 200 K (Martian ice sheet); refrigerator efficiency = 25% of Carnot
4) Compressor efficiency = 50%; ln p_2/p_1 = 5/1
5) 2% efficiency; electricity to food.

Figure 4.4.1 ALPH Flowsheet for Fuels and Propellant Production

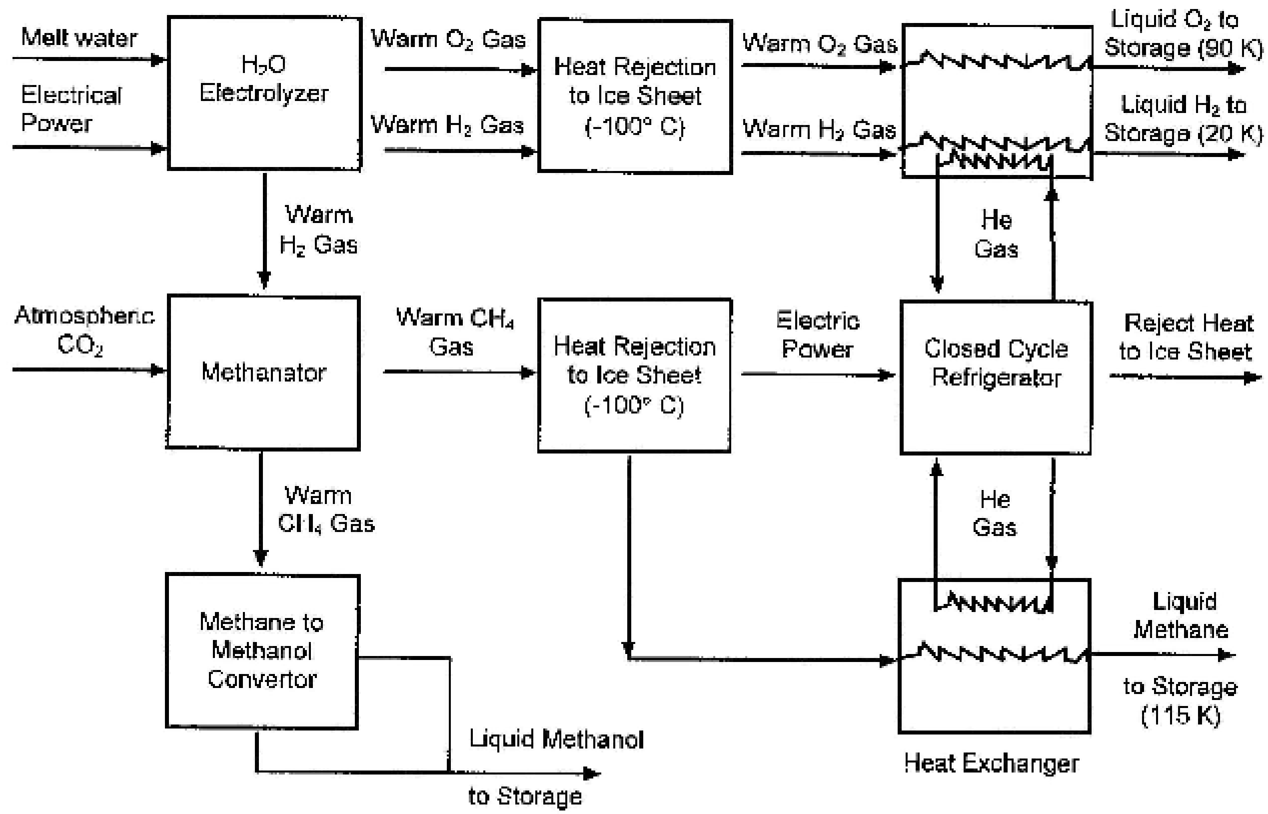


Figure 4.5.1 Flowsheet for Breathable Air Production

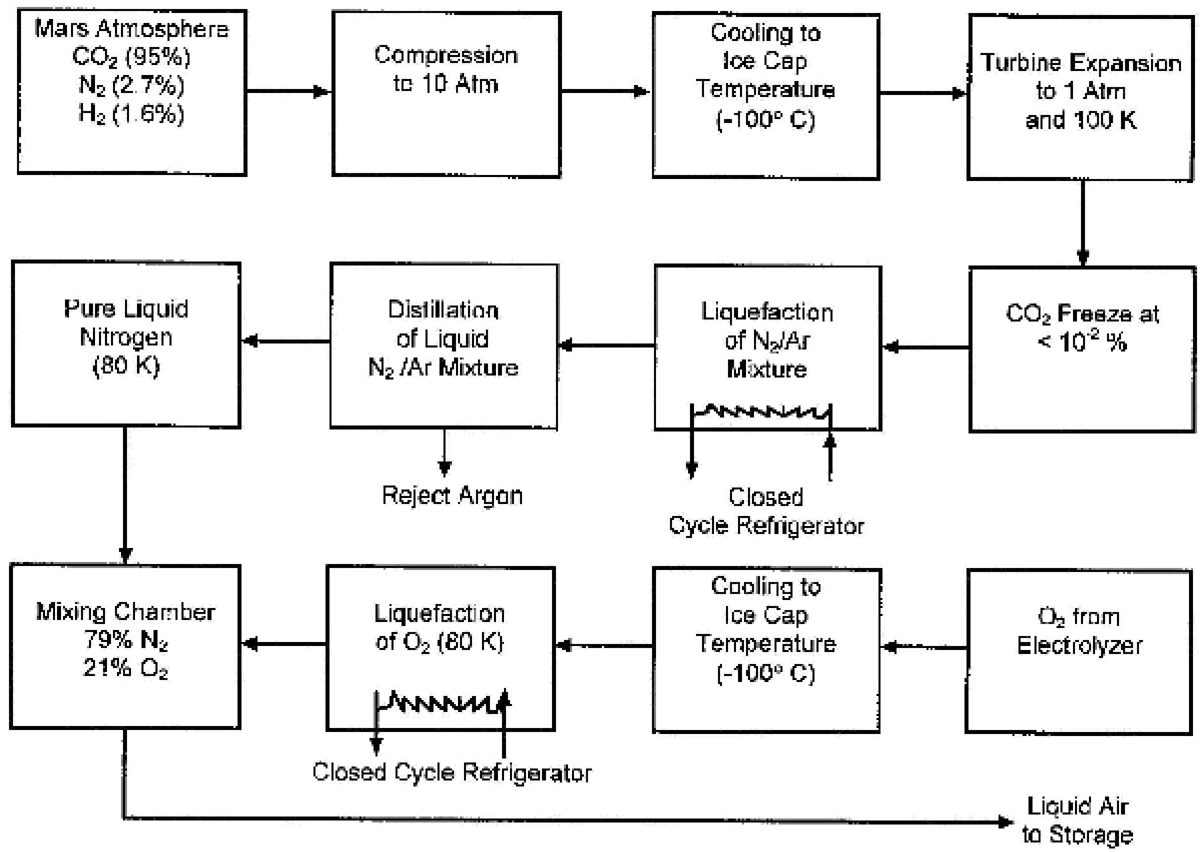


Figure 4.6.1   ALPH Flowsheet for Construction Materials

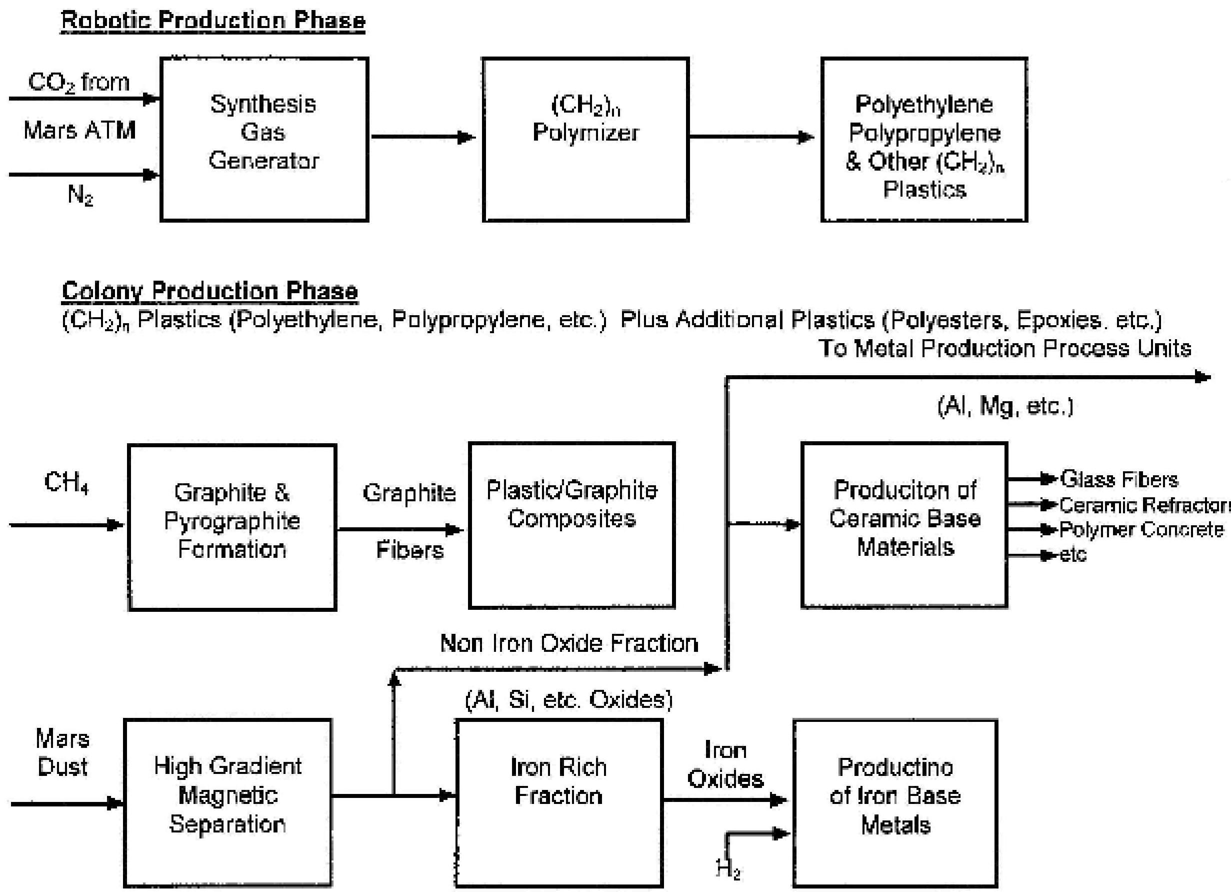


Figure 4.8.1 ALPH Flowsheet for Production

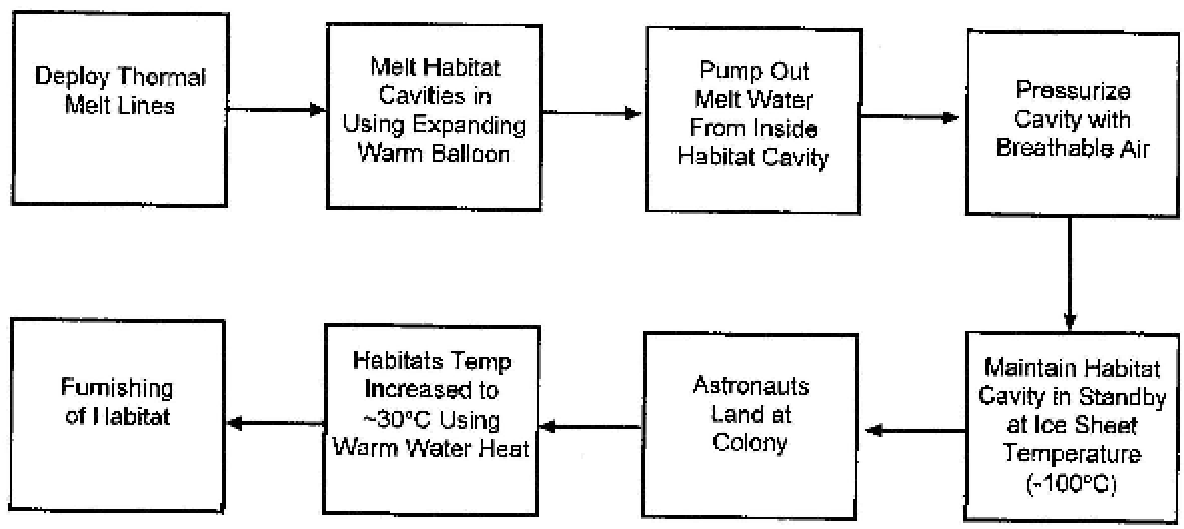


Figure 4.9.1

Time Line for ALPH Operations on Mars

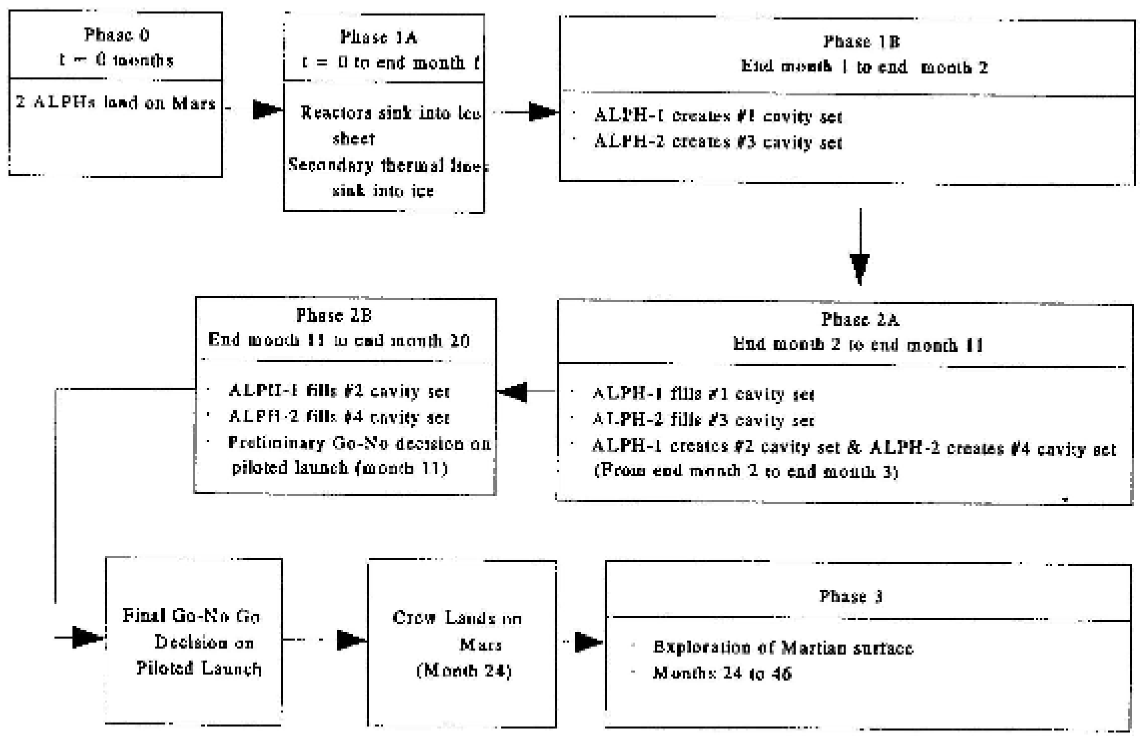


Figure 5.1.1

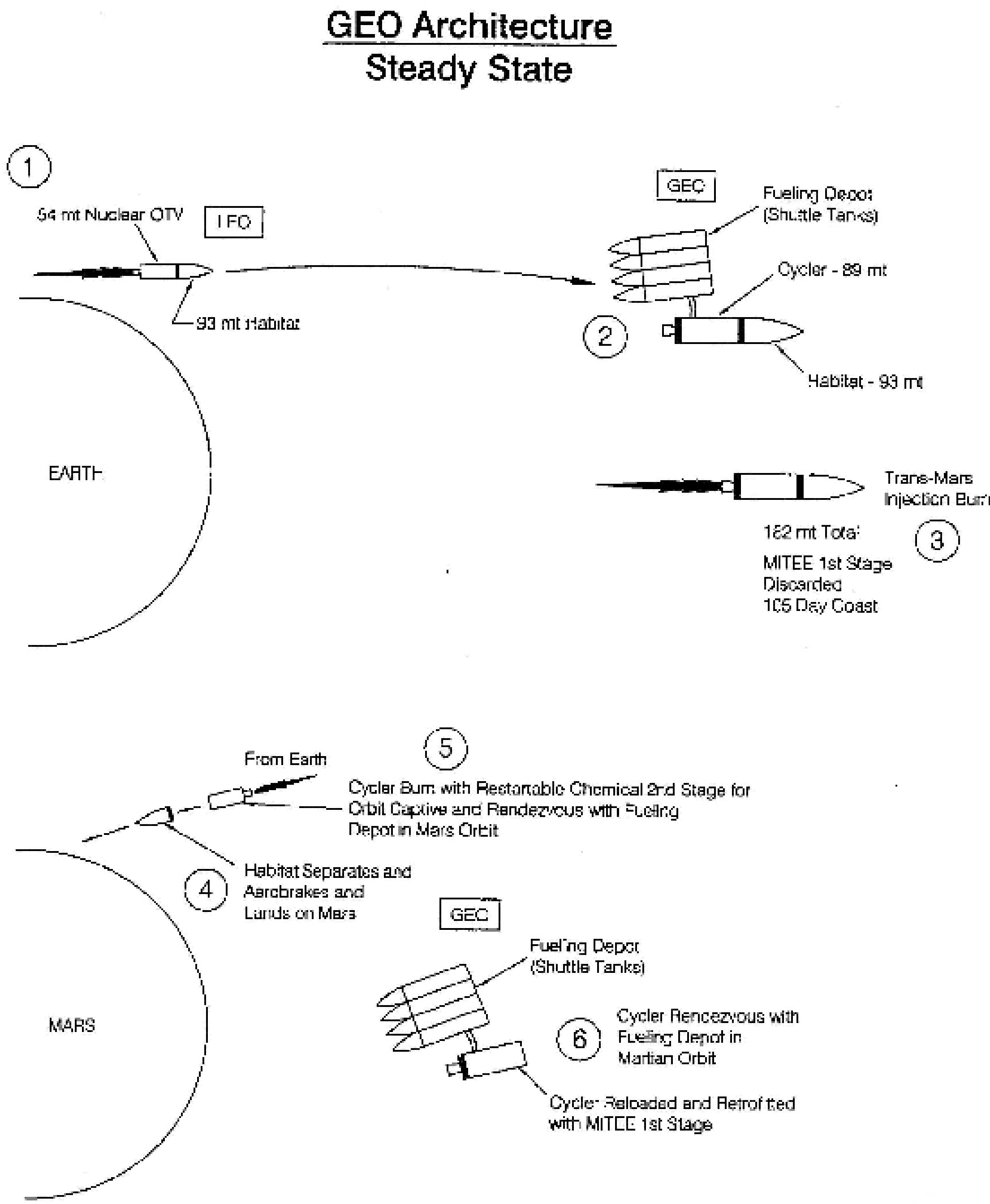

GEO Architecture
Steady State
1
54 mt Nuclear OTV
LEO
93 mt Habitat
GEO
Fueling Depot
(Shuttle Tanks)
Cycler - 89 mt
2
Habitat - 93 mt
EARTH
Trans-Mars
Injection Burn
182 mt Total
3
MITEE 1st Stage
Discarded
105 Day Coast
From Earth
5
Cycler Burn with Restartable Chemical 2nd Stage for
Orbit Captive and Rendezvous with Fueling
Depot in Mars Orbit
Habitat Separates and
Aerobrakes and
Lands on Mars
4
GEO
MARS
Fueling Depot
(Shuttle Tanks)
Cycler Rendezvous with
Fueling Depot in
Martian Orbit
6
Cycler Reloaded and Retrofitted
with MITEE 1st Stage

Figure 5.1.2

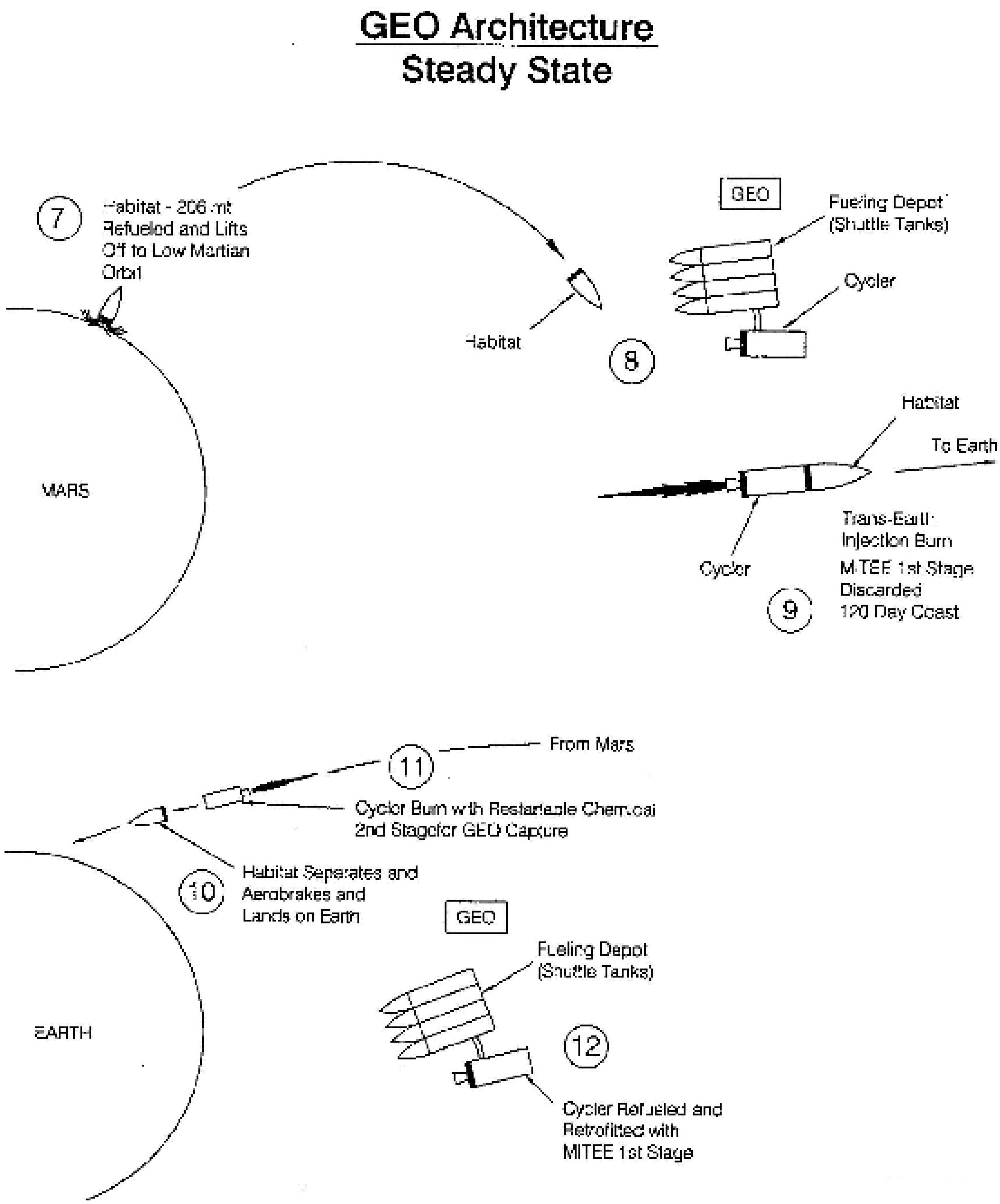
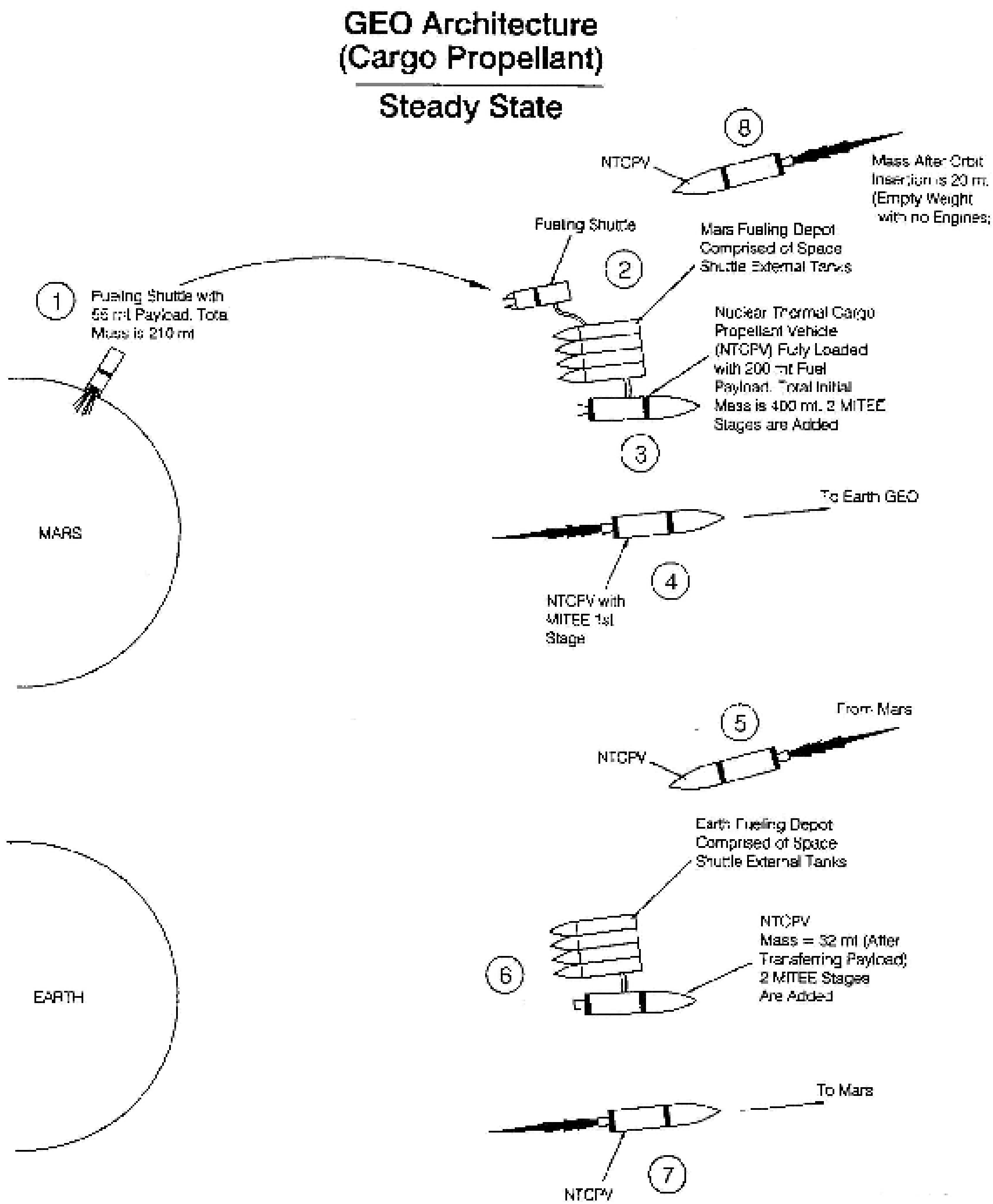

GEO Architecture
Steady State
7
Habitat - 206 mt
Refueled and Lifts
Off to Low Martian
Orbit
MARS
Habitat
8
GEO
Fueling Depot
(Shuttle Tanks)
Cycler
Habitat
To Earth
Trans-Earth
Injection Burn
MITEE 1st Stage
Discarded
120 Day Coast
Cycler
9
From Mars
11
Cycler Burn with Restartable Chemical
2nd Stage for GEO Capture
Habitat Separates and
Aerobrakes and
Lands on Earth
10
GEO
EARTH
Fueling Depot
(Shuttle Tanks)
12
Cycler Refueled and
Retrofitted with
MITEE 1st Stage

Figure 5.1.3



GEO Architecture
(Cargo Propellant)
Steady State
8
NTCPV
Mass After Orbit Insertion is 20 mt. (Empty Weight with no Engines)
Fueling Shuttle
2
Mars Fueling Depot Comprised of Space Shuttle External Tanks
1
Fueling Shuttle with 55 mt Payload. Total Mass is 210 mt
Nuclear Thermal Cargo Propellant Vehicle (NTCPV) Fully Loaded with 200 mt Fuel Payload. Total Initial Mass is 400 mt. 2 MITEE Stages are Added
3
MARS
To Earth GEO
4
NTCPV with MITEE 1st Stage
5
From Mars
NTCPV
Earth Fueling Depot Comprised of Space Shuttle External Tanks
NTCPV Mass = 32 mt (After Transferring Payload) 2 MITEE Stages Are Added
6
EARTH
To Mars
7
NTCPV

Figure 5.1.4

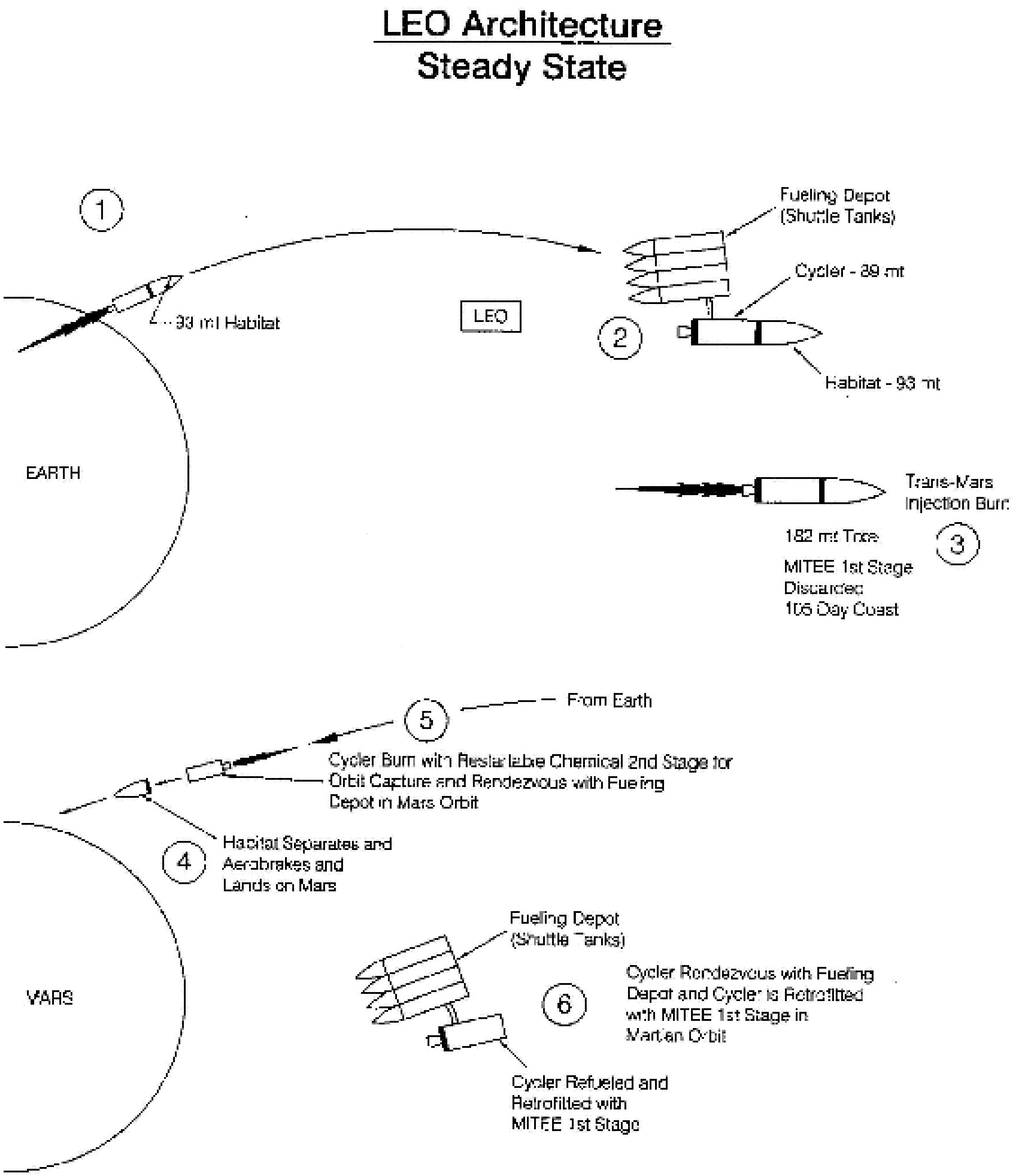
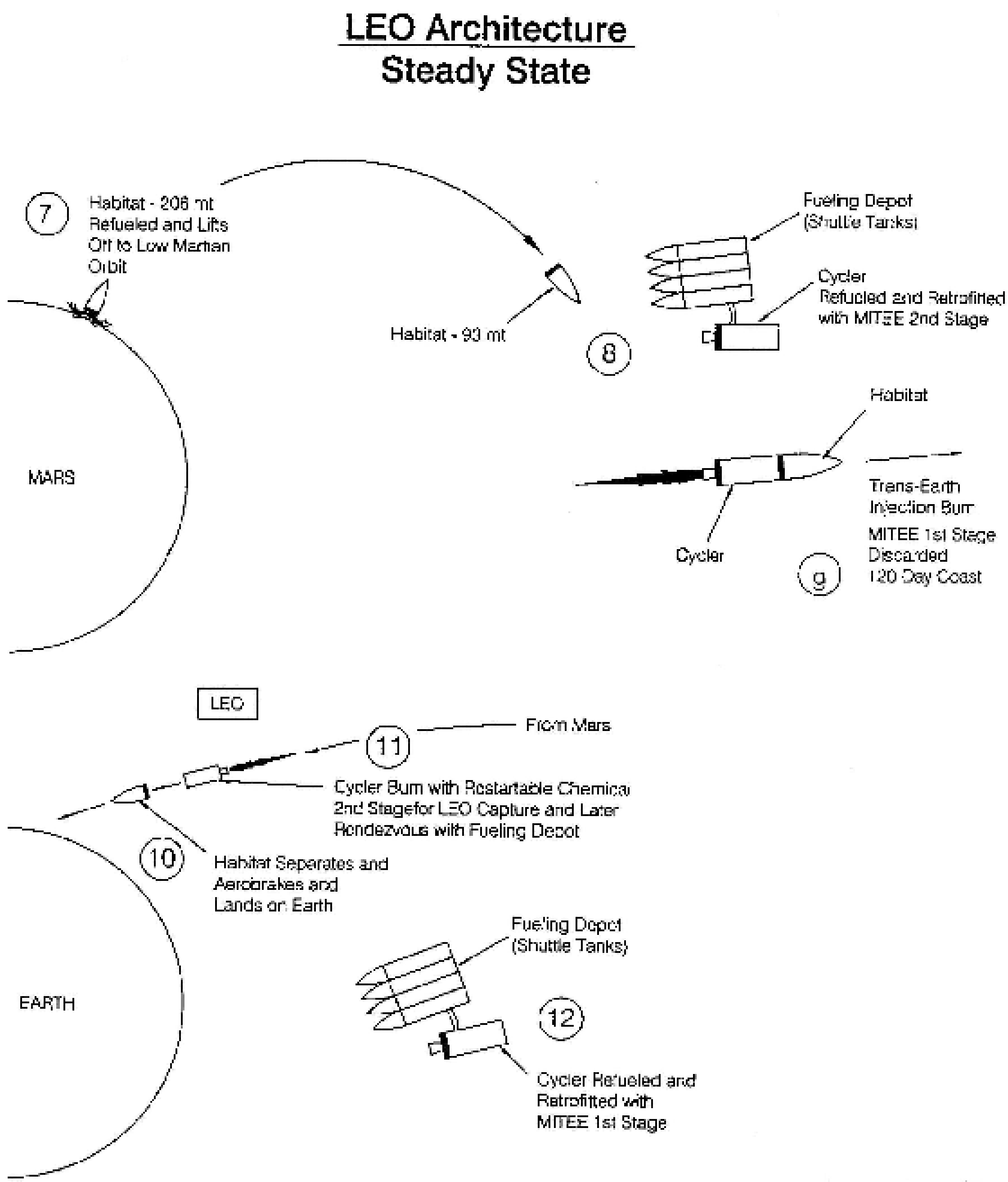

LEO Architecture
Steady State
1
93 mt Habitat
LEO
Fueling Depot
(Shuttle Tanks)
Cycler - 89 mt
2
Habitat - 93 mt
EARTH
Trans-Mars
Injection Burn
3
MITEE 1st Stage
Discarded
106 Day Coast
5
From Earth
Cycler Burn with Restartable Chemical 2nd Stage for
Orbit Capture and Rendezvous with Fueling
Depot in Mars Orbit
4
Habitat Separates and
Aerobrakes and
Lands on Mars
MARS
Fueling Depot
(Shuttle Tanks)
6
Cycler Rendezvous with Fueling
Depot and Cycler is Retrofitted
with MITEE 1st Stage in
Martian Orbit
Cycler Refueled and
Retrofitted with
MITEE 1st Stage

Figure 5.1.5



LEO Architecture
Steady State
7
Habitat - 206 mt
Refueled and Lifts
Off to Low Martian
Orbit
MARS
Habitat - 93 mt
8
Fueling Depot
(Shuttle Tanks)
Cycler
Refueled and Retrofitted
with MITEE 2nd Stage
Habitat
Trans-Earth
Injection Burn
MITEE 1st Stage
Discarded
120 Day Coast
Cycler
9
LEO
From Mars
11
Cycler Burn with Restartable Chemical
2nd Stage for LEO Capture and Later
Rendezvous with Fueling Depot
10
Habitat Separates and
Aerobrakes and
Lands on Earth
EARTH
Fueling Depot
(Shuttle Tanks)
12
Cycler Refueled and
Retrofitted with
MITEE 1st Stage

Figure 5.1.6

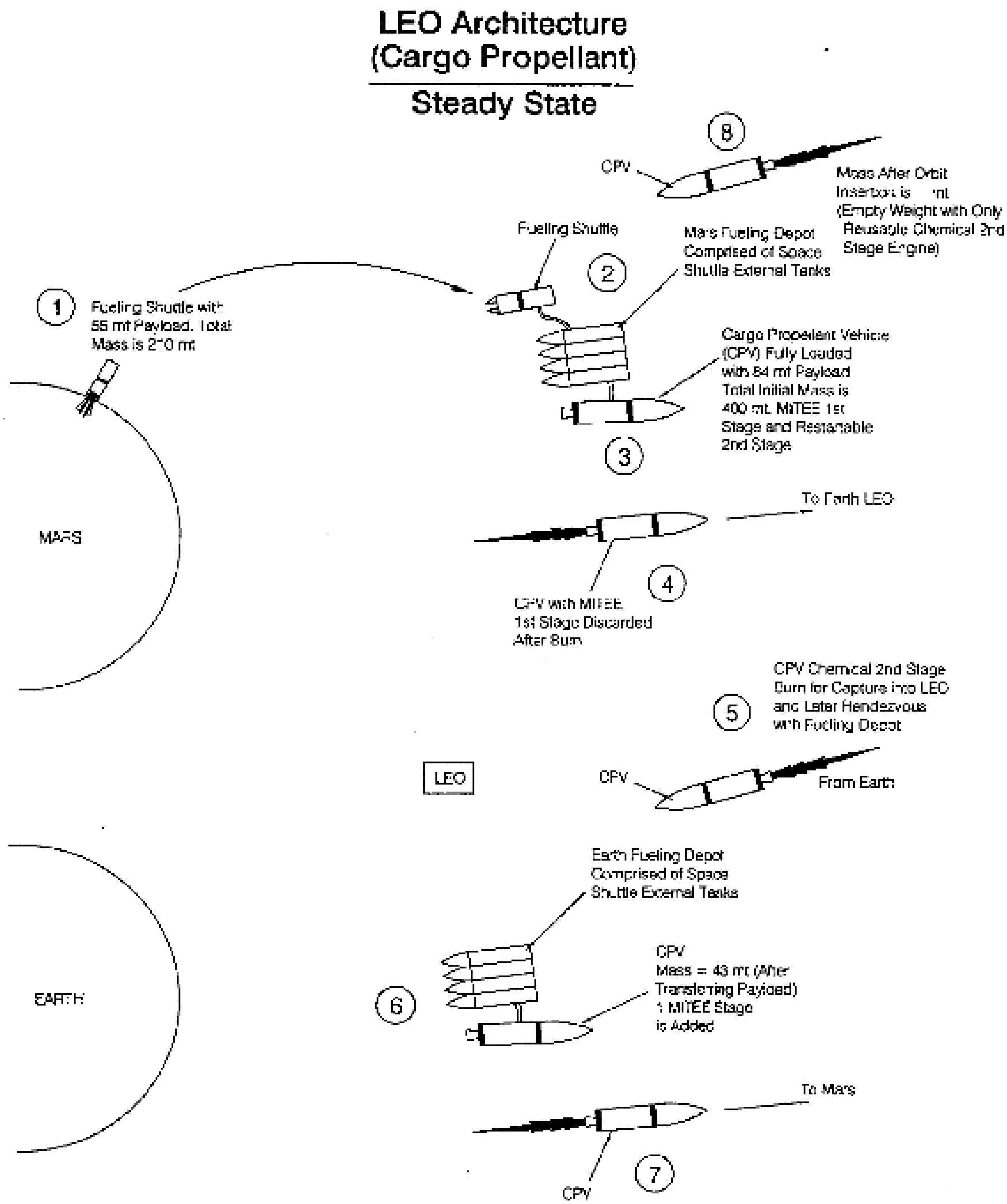

LEO Architecture
(Cargo Propellant)
Steady State
8
CPV
Mass After Orbit Insertion is mt (Empty Weight with Only Reusable Chemical 2nd Stage Engine)
Fueling Shuttle
2
Mars Fueling Depot Comprised of Space Shuttle External Tanks
1
Fueling Shuttle with 55 mt Payload. Total Mass is 2?0 mt
Cargo Propellant Vehicle (CPV) Fully Loaded with 84 mt Payload Total Initial Mass is 400 mt. MITEE 1st Stage and Restartable 2nd Stage
3
MARS
To Earth LEO
4
CPV with MITEE 1st Stage Discarded After Burn
CPV Chemical 2nd Stage Burn for Capture into LEO and Later Rendezvous with Fueling Depot
5
LEO
CPV
From Earth
Earth Fueling Depot Comprised of Space Shuttle External Tanks
CPV Mass = 43 mt (After Transferring Payload) 1 MITEE Stage is Added
EARTH
6
To Mars
CPV
7

Figure 5.1.7

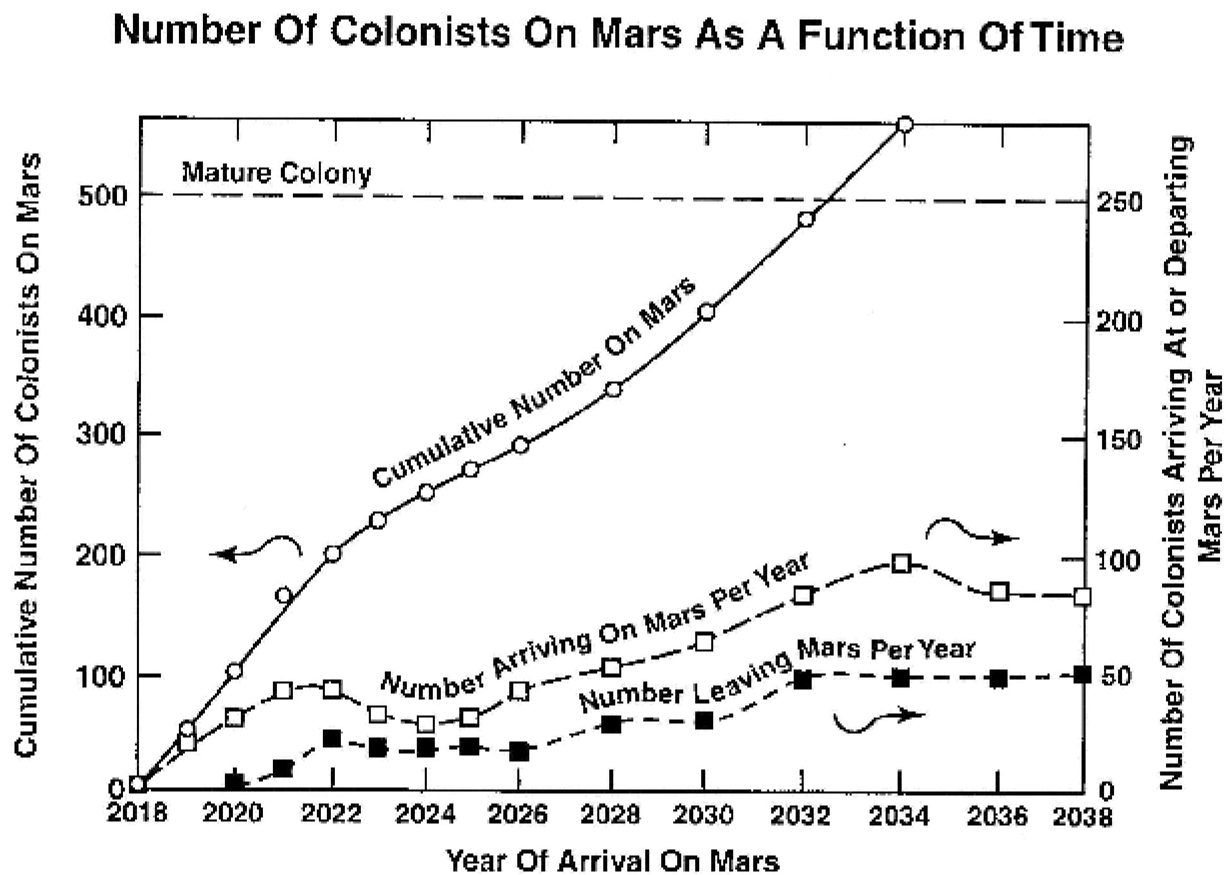

Number Of Colonists On Mars As A Function Of Time
Mature Colony
Cumulative Number On Mars
Number Arriving On Mars Per Year
Number Leaving Mars Per Year
Cumulative Number Of Colonists On Mars
Number Of Colonists Arriving At or Departing Mars Per Year
Year Of Arrival On Mars
0
100
200
300
400
500
0
50
100
150
200
250
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038

Figure 5.1.8

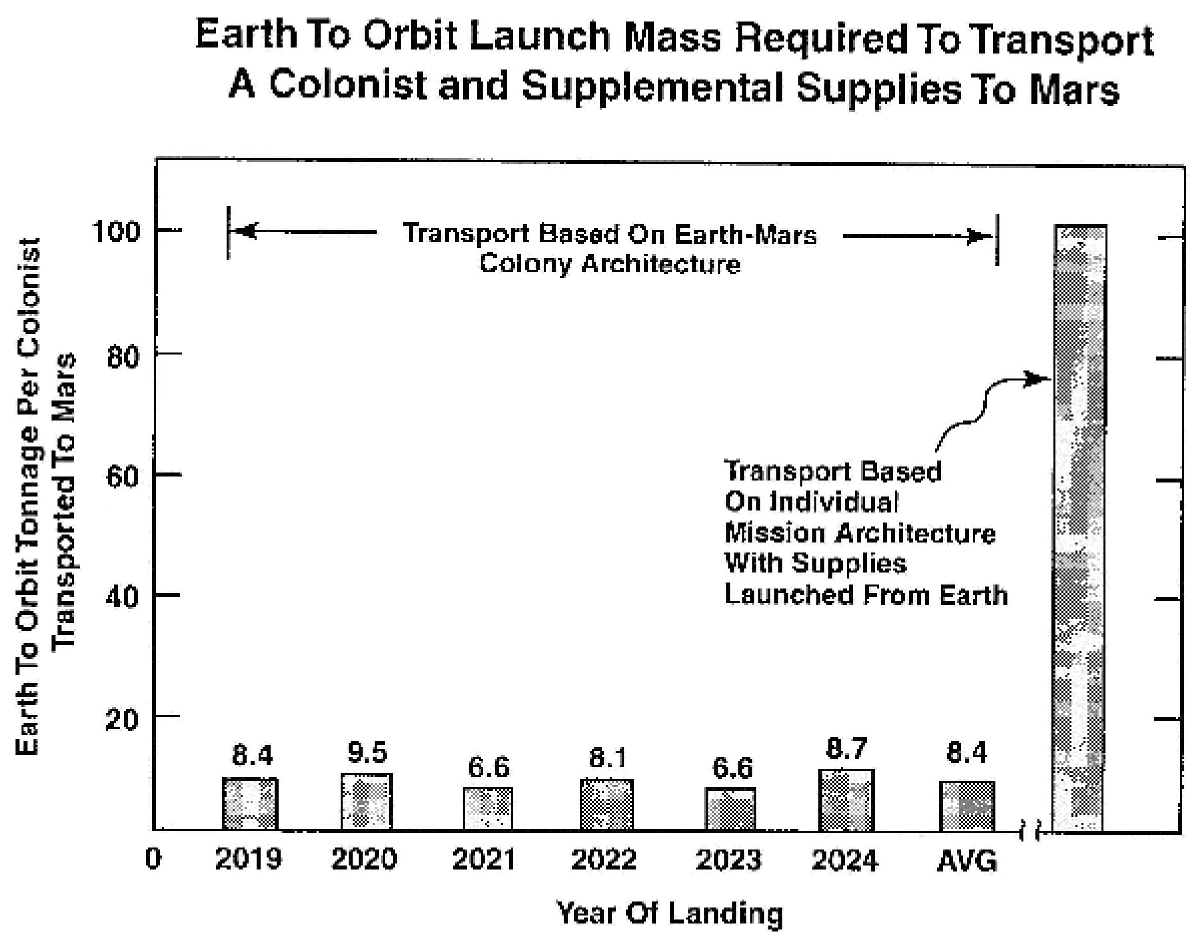

Earth To Orbit Launch Mass Required To Transport
A Colonist and Supplemental Supplies To Mars
Earth To Orbit Tonnage Per Colonist
Transported To Mars
100
80
60
40
20
0
Transport Based On Earth-Mars
Colony Architecture
Transport Based
On Individual
Mission Architecture
With Supplies
Launched From Earth
8.4
9.5
6.6
8.1
6.6
8.7
8.4
2019
2020
2021
2022
2023
2024
AVG
Year Of Landing

Figure 5.1.9

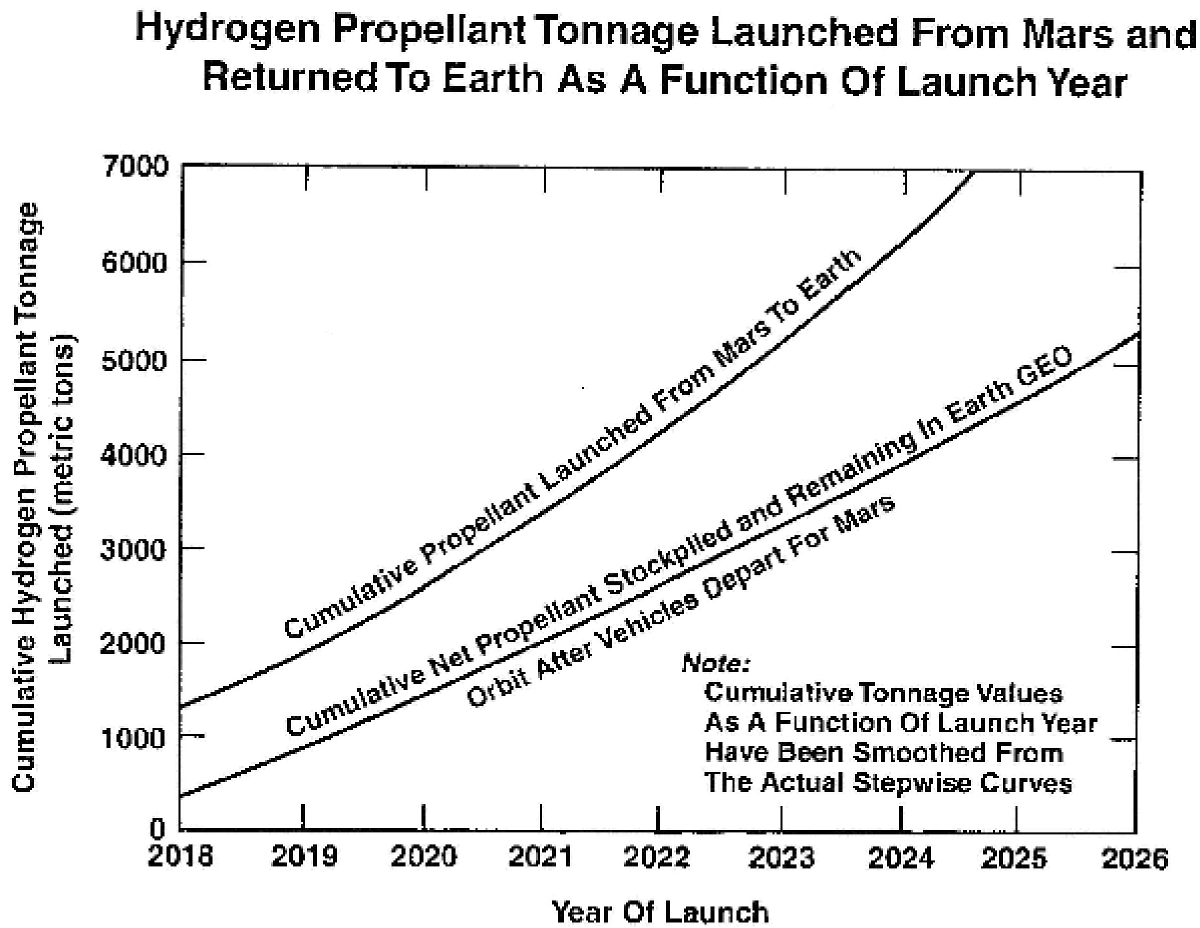
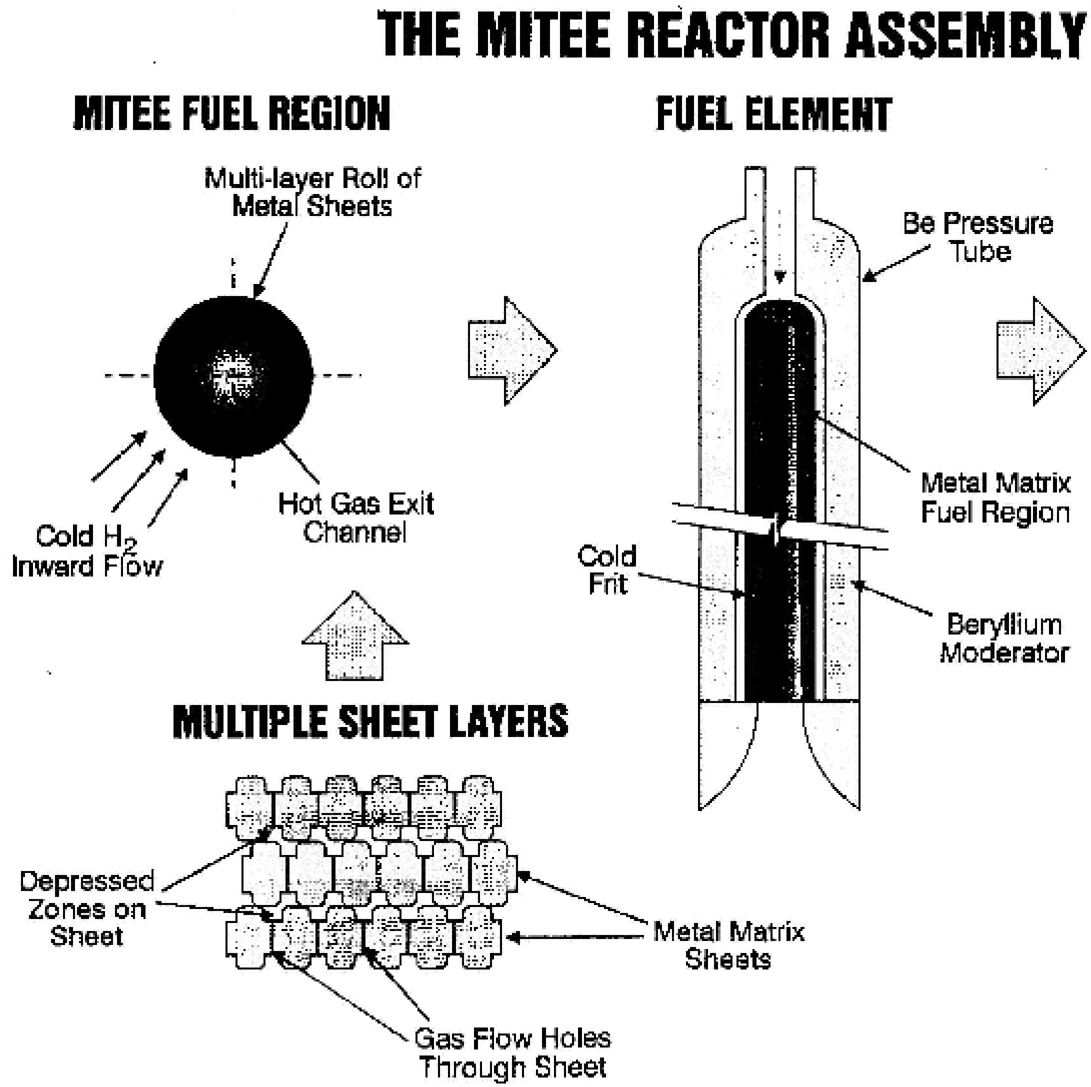
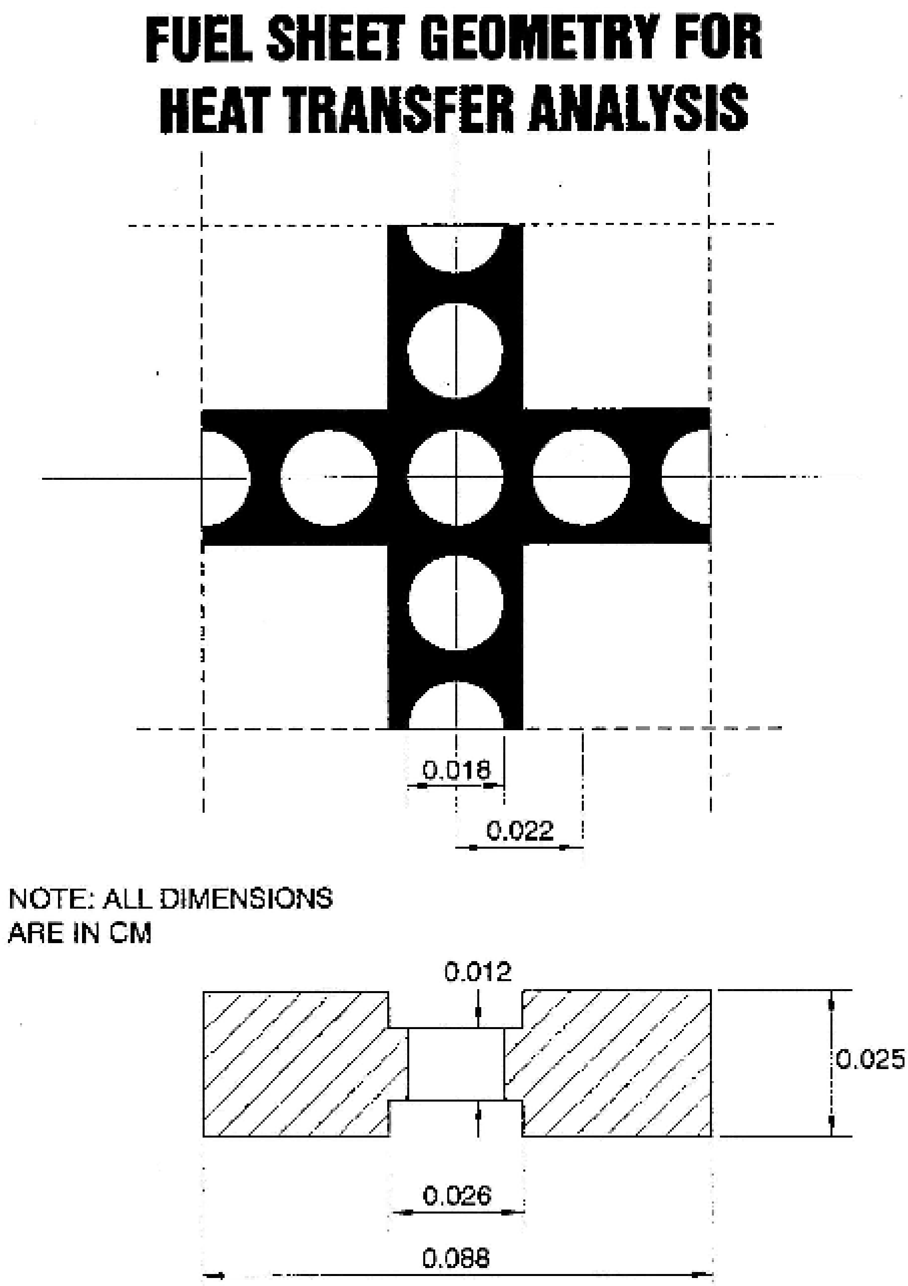

Hydrogen Propellant Tonnage Launched From Mars and Returned To Earth As A Function Of Launch Year
Cumulative Hydrogen Propellant Tonnage Launched (metric tons)
0
1000
2000
3000
4000
5000
6000
7000
2018
2019
2020
2021
2022
2023
2024
2025
2026
Year Of Launch
Cumulative Propellant Launched From Mars To Earth
Cumulative Net Propellant Stockpiled and Remaining In Earth GEO Orbit After Vehicles Depart For Mars
Note:
Cumulative Tonnage Values As A Function Of Launch Year Have Been Smoothed From The Actual Stepwise Curves

Figure 5.2.1

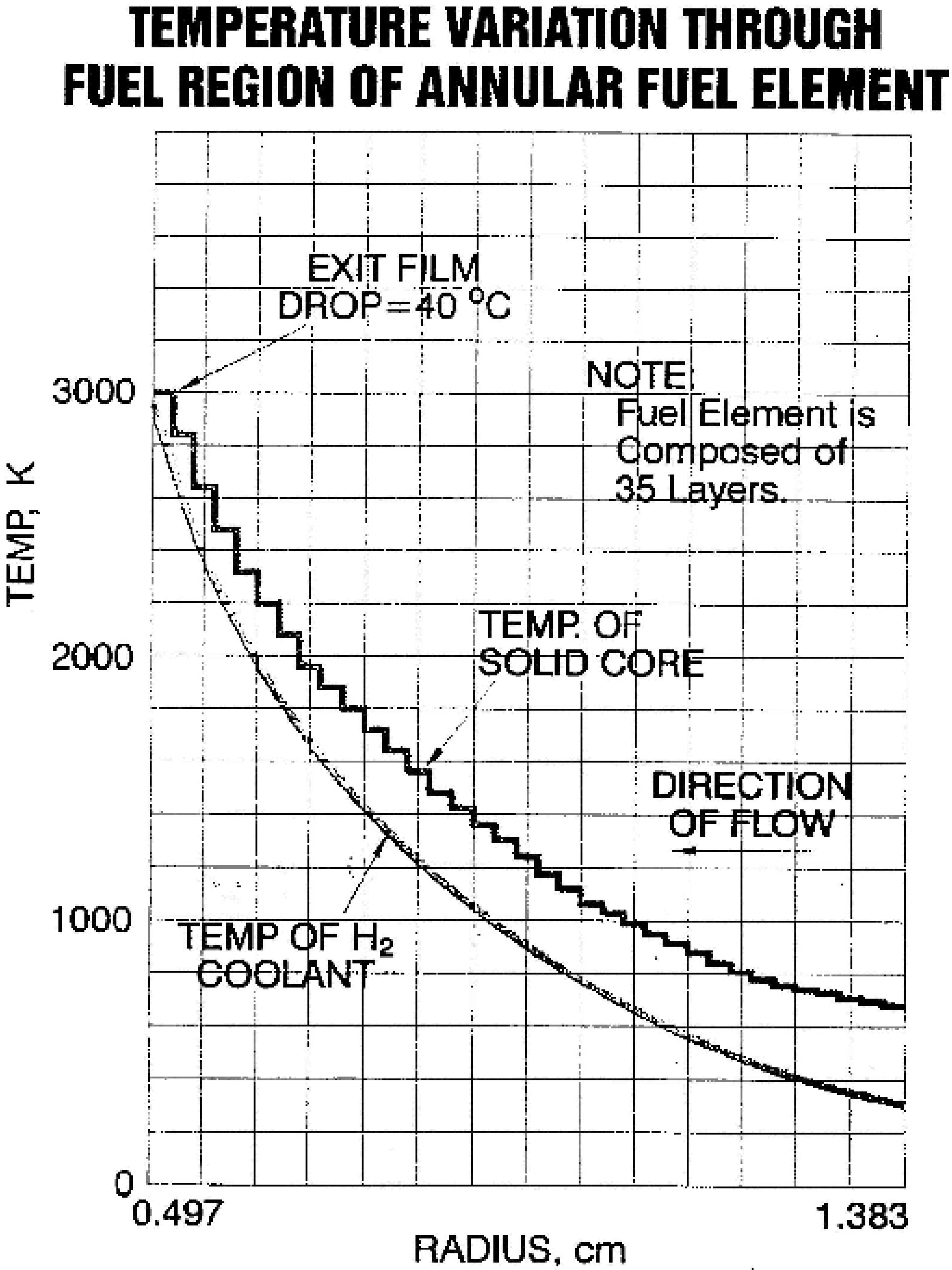

THE MITEE REACTOR ASSEMBLY
MITEE FUEL REGION
Multi-layer Roll of Metal Sheets
Hot Gas Exit Channel
Cold H_2 Inward Flow
FUEL ELEMENT
Be Pressure Tube
Metal Matrix Fuel Region
Cold Frit
Beryllium Moderator
MULTIPLE SHEET LAYERS
Depressed Zones on Sheet
Metal Matrix Sheets
Gas Flow Holes Through Sheet

Fogire 5.2.2



FUEL SHEET GEOMETRY FOR
HEAT TRANSFER ANALYSIS
0.018
0.022
NOTE: ALL DIMENSIONS
ARE IN CM
0.012
0.025
0.026
0.088

Figure 5.2.3



TEMPERATURE VARIATION THROUGH FUEL REGION OF ANNULAR FUEL ELEMENT
EXIT FILM DROP=40 °C
NOTE: Fuel Element is Composed of 35 Layers.
TEMP. OF SOLID CORE
DIRECTION OF FLOW
TEMP OF H2 COOLANT
3000
2000
1000
0
TEMP, K
0.497
1.383
RADIUS, cm

Figure 5.2.4

VARIATION OF MULTIPLICATION FACTOR AND MASS WITH MITEE REACTOR FUEL ELEMENT PITCH/DIAMETER RATIO

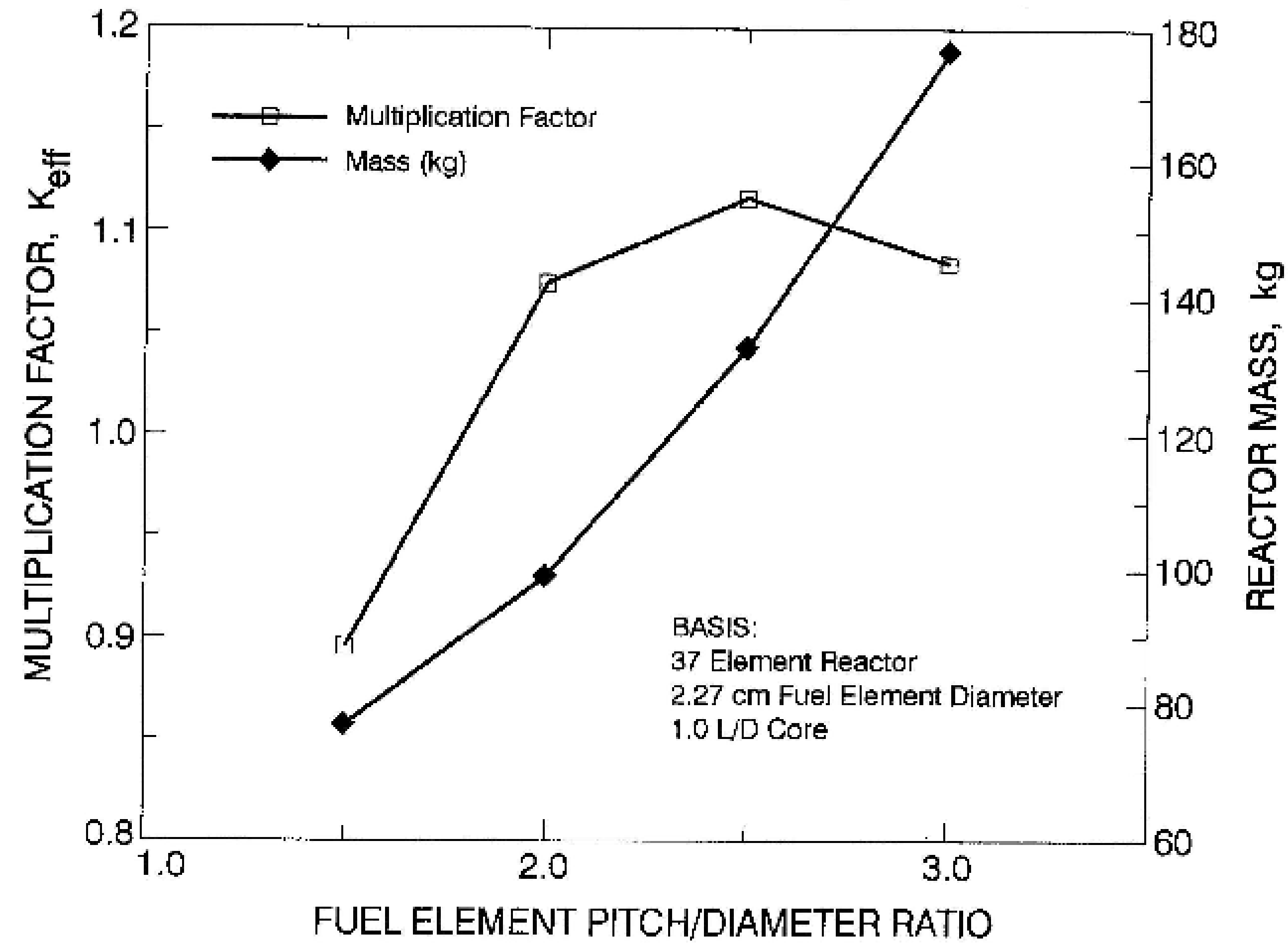


Figure 5.2.5

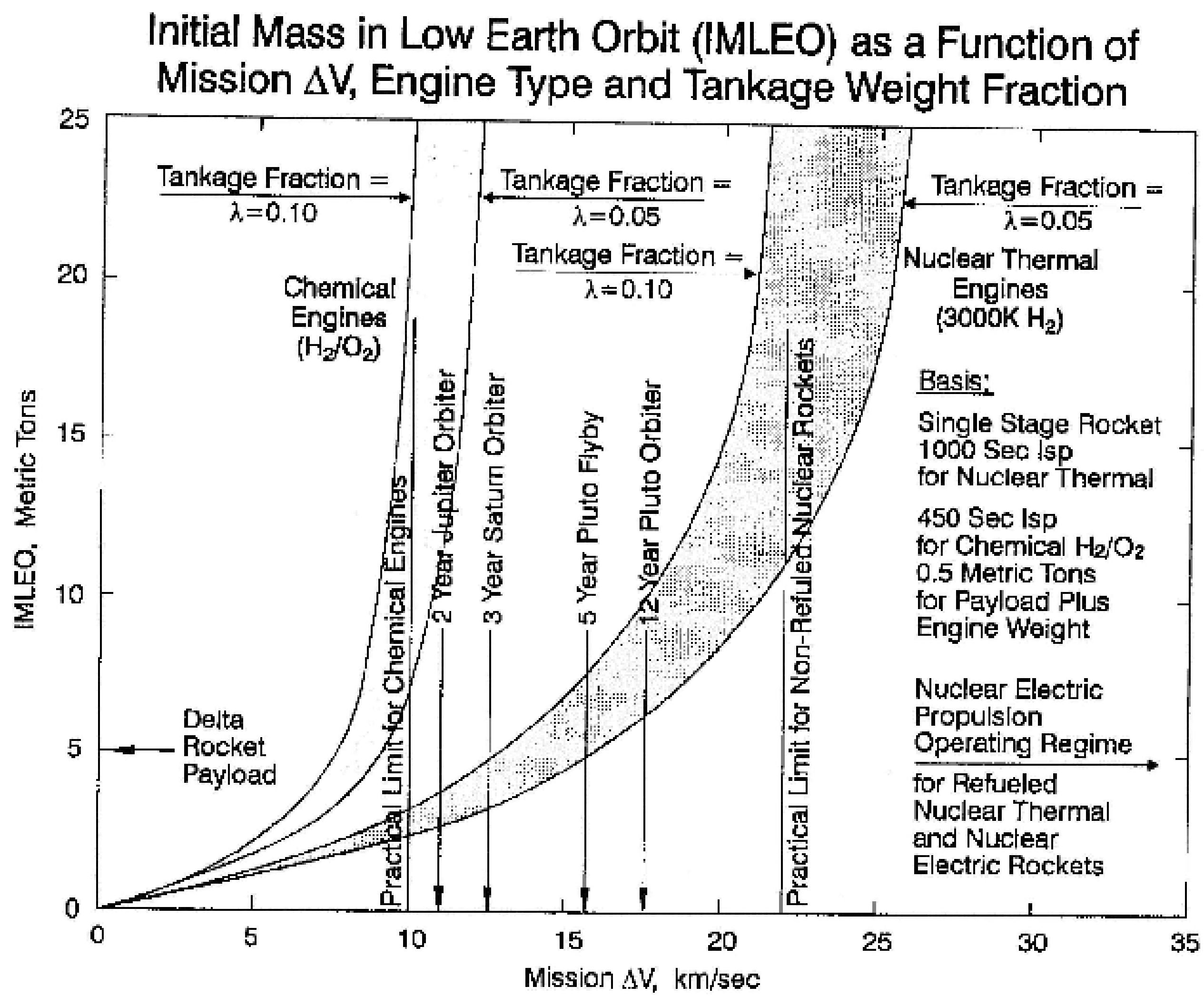
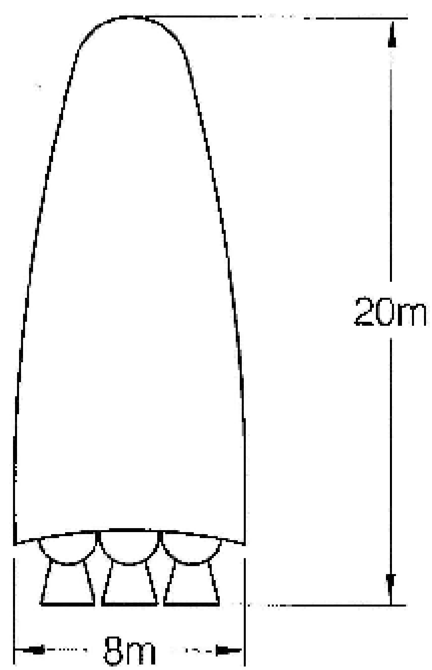

Initial Mass in Low Earth Orbit (IMLEO) as a Function of Mission ΔV, Engine Type and Tankage Weight Fraction
IMLEO, Metric Tons
Mission ΔV, km/sec
0
5
10
15
20
25
30
35
Tankage Fraction = λ=0.10
Chemical Engines (H_2/O_2)
Tankage Fraction = λ=0.05
Tankage Fraction = λ=0.10
Tankage Fraction = λ=0.05
Nuclear Thermal Engines (3000K H_2)
Delta Rocket Payload
Practical Limit for Chemical Engines
2 Year Jupiter Orbiter
3 Year Saturn Orbiter
5 Year Pluto Flyby
12 Year Pluto Orbiter
Practical Limit for Non-Refueled Nuclear Rockets
Basis:
Single Stage Rocket
1000 Sec Isp
for Nuclear Thermal
450 Sec Isp
for Chemical H_2/O_2
0.5 Metric Tons
for Payload Plus
Engine Weight
Nuclear Electric Propulsion Operating Regime
for Refueled Nuclear Thermal and Nuclear Electric Rockets

Figure 5.3.1

Mars Infrastructure Flotilla

Habitat



$Weight_{Empty}$ = 57 Tons

$Weight_{Full}$ = 71 Tons
(ΔV = 1 Km/sec)

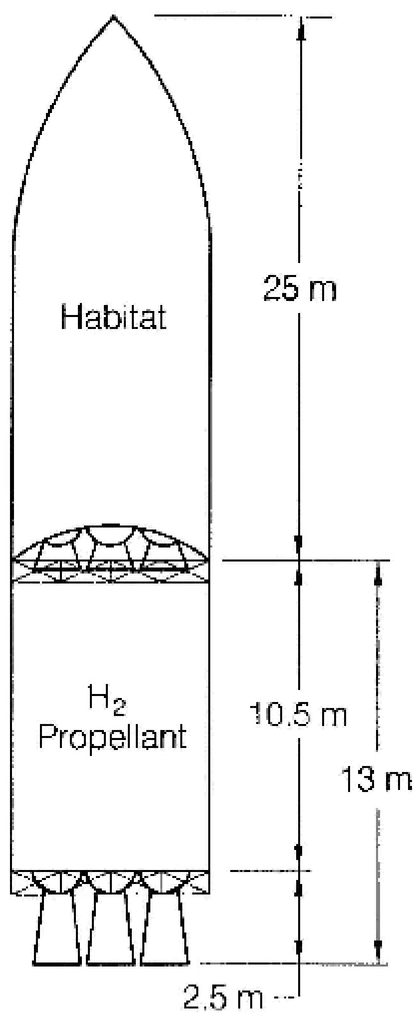
$Weight_{Full}$ = 93 Tons
(ΔV = 2.2 Km/sec)

Isp = 450 sec

Crew = 22 People

New H_2/O_2 Engine

Figure 5.3.2



Mars Infrastructure Flotilla

NPT OTV (From Lifting Habitat to GEO)

Weight $_{Empty}$ = 4.0 Tons

Weight $_{Full}$ (No Payload) = 51.0 Tons

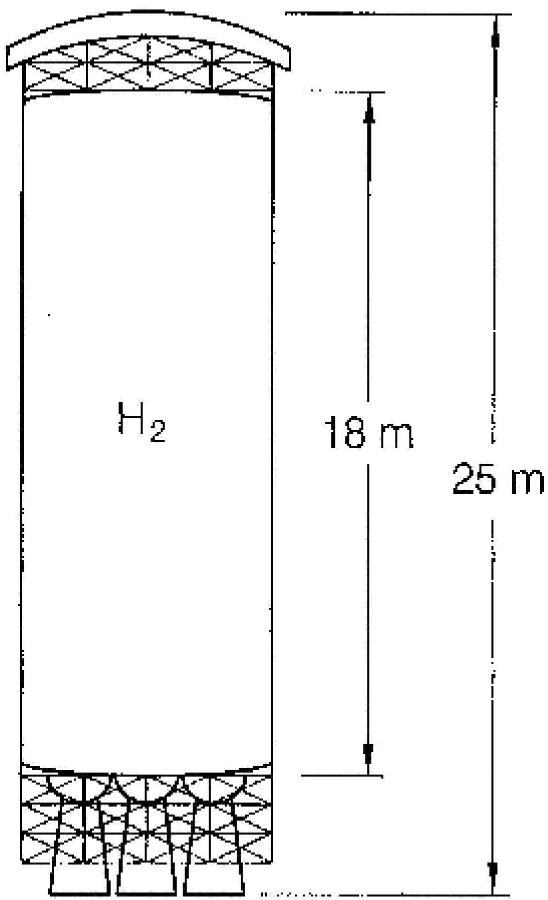
Weight $_{Full}$ (With 93 Ton Habitat Payload) = 144 Tons

Isp = 1050 sec

MITEE Engine

Mars Infrastructure Flotilla

Cycler (Both Stages Nuclear)



$\text{Weight}_{\text{Empty}}$ = 8.9 Tons

$\text{Weight}_{\text{Full}}$ = 77 Tons (No Payload)

$\text{Weight}_{\text{Full}}$ = 170 Tons (With 93 Ton Habitat Payload)

Isp = 1050 sec 1st Stage

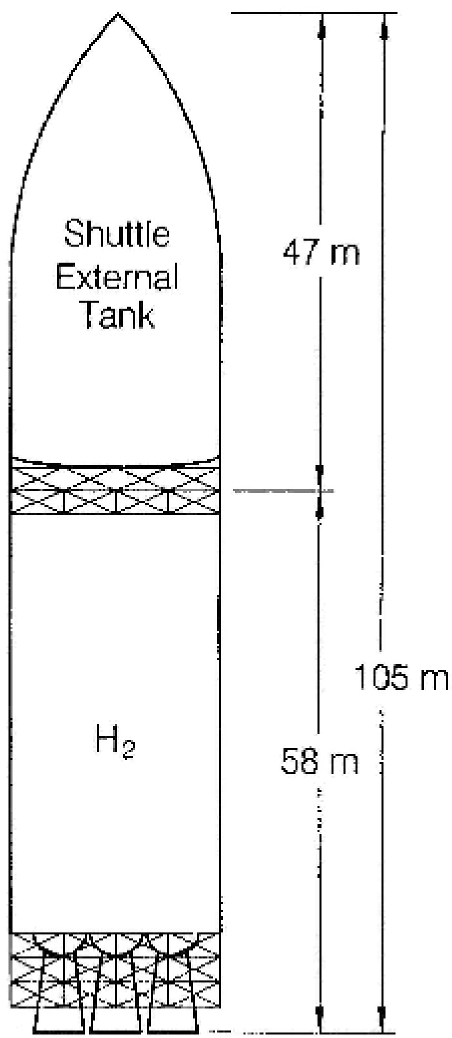
MITEE Engines for Each Stage

9-00-9

Figure 5.3.4

Mars Infrastructure Flotilla

Alternate Cargo Propellant Vehicle
(All Nuclear Stages)



Weight $_{Empty}$ = 41.5 Tons
(Empty Shuttle E.T.)

Weight $_{Full}$ = 251 Tons
(No Payload in Shuttle E.T.)

Weight $_{Full}$ = 436 Tons
(With 185 Ton Payload in E.T.)

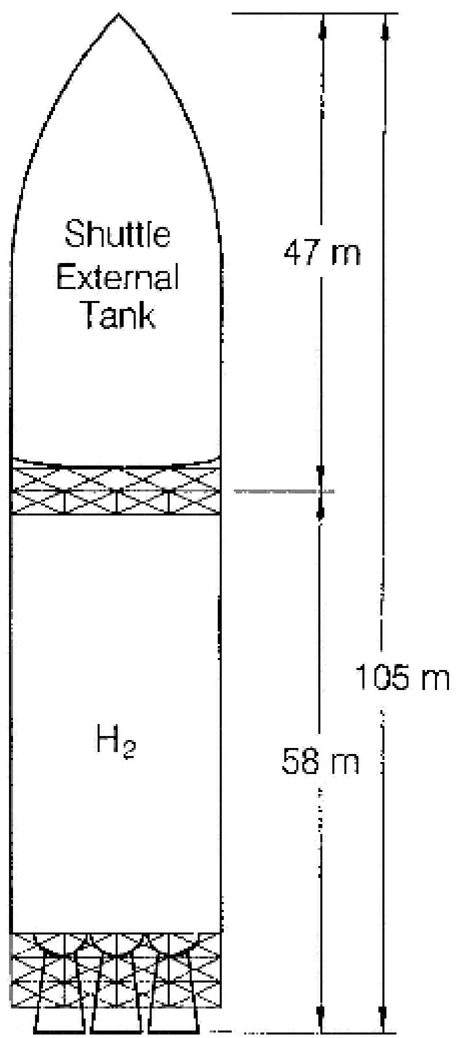
Isp = 1050 sec

MITEE Engine for Each Stage

Figure 5.3.5

Mars Infrastructure Flotilla

Alternate Cargo Propellant Vehicle (All Nuclear Stages)



Weight $_{Empty}$ = 41.5 Tons
(Empty Shuttle E.T.)

Weight $_{Full}$ = 251 Tons
(No Payload in Shuttle E.T.)

Weight $_{Full}$ = 436 Tons
(With 185 Ton Payload in E.T.)

Isp = 1050 sec

MITEE Engine for Each Stage

Figure 6.1.1

Functions and Activities in Xanadu

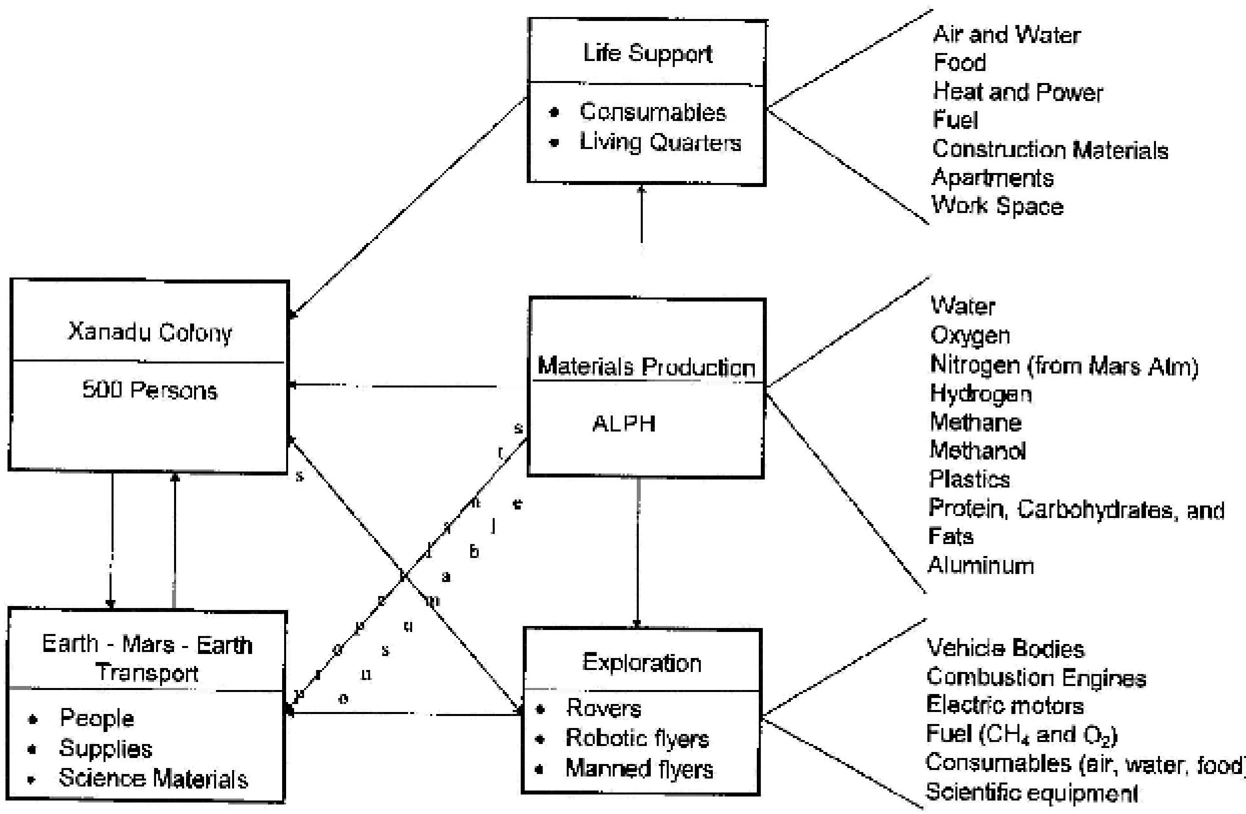


Figure 6.1.2

An Excellent Quality of Life in Xanadu is Possible

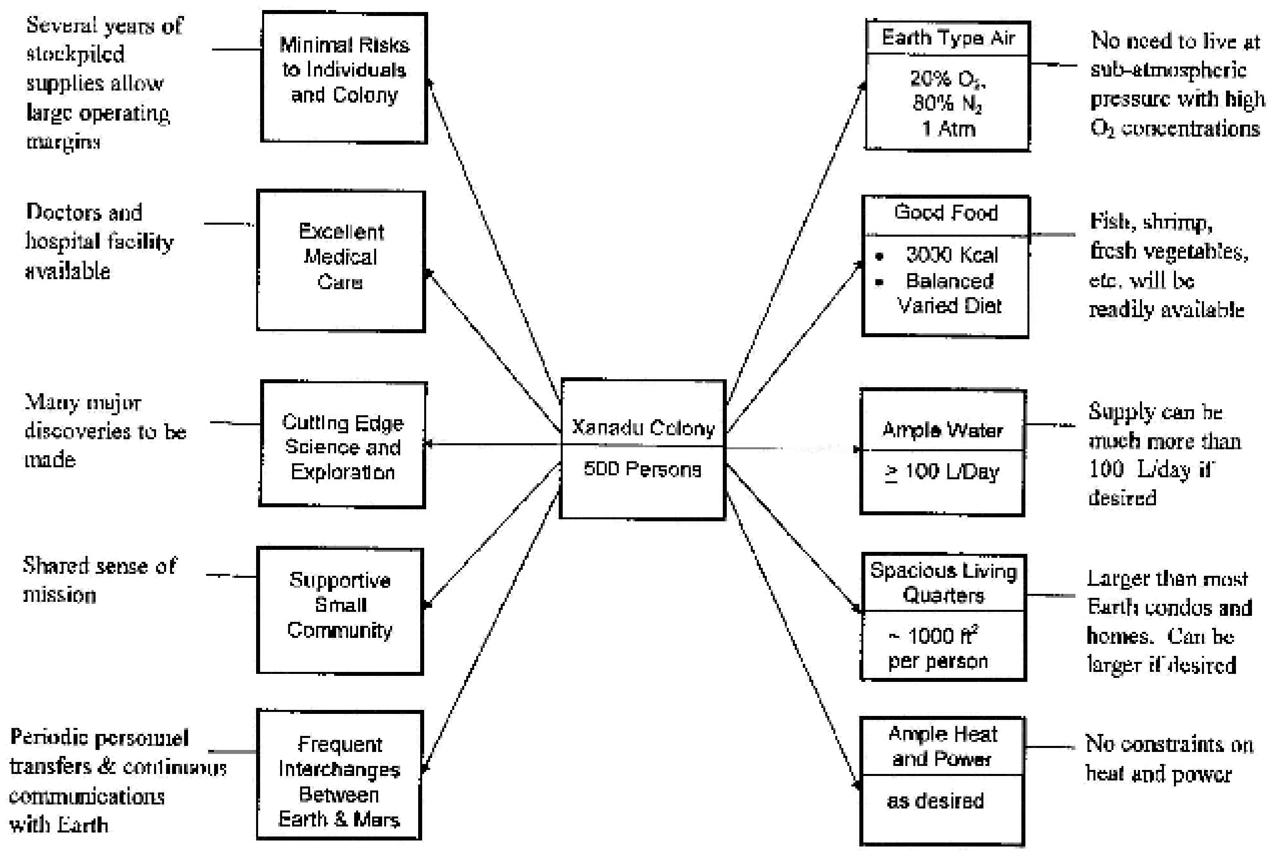


Figure 6.1.3

Life Support Requirements for Xanadu

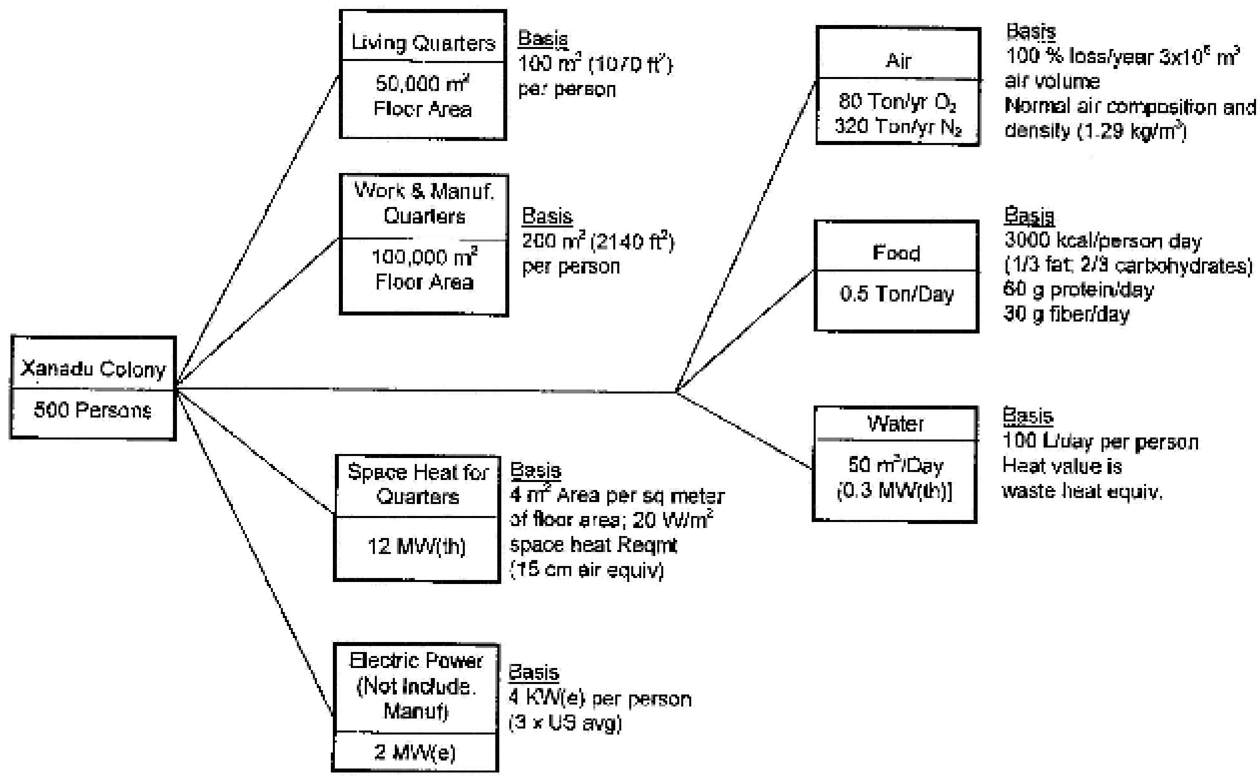


Figure 6.2.1
Exploration Modes for Xanadu

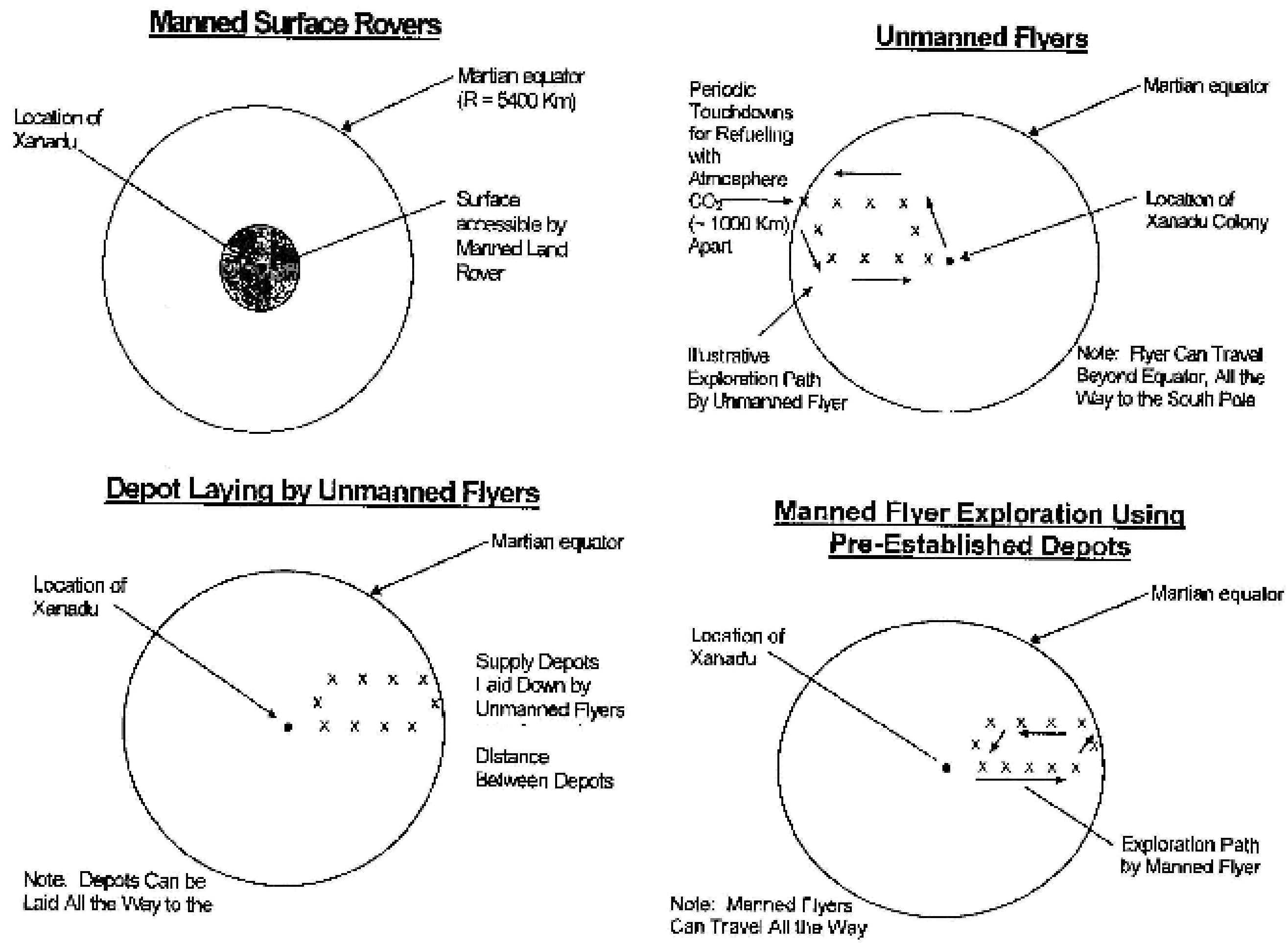


Figure 6.2.2

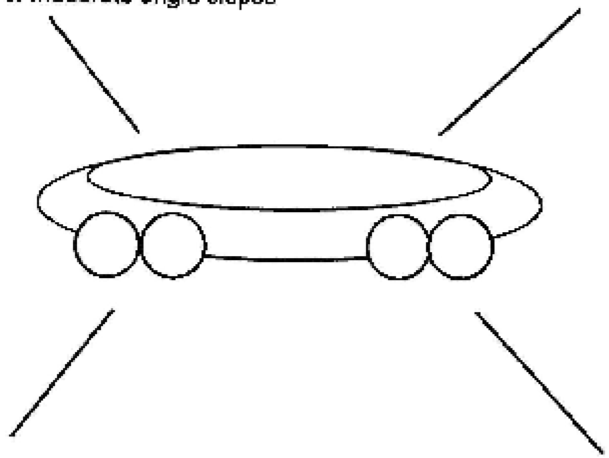
Manned Ice Cap Rover - Features and Requirements

Type of Terrain

- Ice and ice/dust frozen surfaces
- Flat or moderate angle slopes

Crew and Equipment

- 2 or 3 person crew
- Pressurized cabin
- Surface and sub-surface sample analysis and collection
- Emplace data recorders (MICE, etc.)
- 300 kg consumable supplies
- 300 kg samples



Traction and Propulsion

- Low contact pressure, large balloon tires
- Liquid CH_4/O_2 fuel
- Turbine engine with electric drive wheels
- 1000 kg empty vehicle mass

Speed and Range

- 50 km/hour maximum speed
- 2000 km maximum range (1000 km out, 1000 km return)
- 2 week maximum trip time
- 4/10 km per MJ of energy (= 40 mpg conv. auto)
- 450 kg CH_4 and O_2 per trip (2000 km)

Figure 6.2.3

Unmanned Flyer Design Features

- Energy source is compact lightweight (100 kg) nuclear reactor
- Uses heated (2000 K) atmospheric CO_2 for propulsive force
- Supersonic flight (M = 2) in Mars atmosphere @ 470 meters / sec (1050 mph)
- Uses stored on-board liquid CO_2 in-flight for propulsion using internal fixed beds of activated carbon particles
  - Bed absorbs CO_2 at ambient temperature, desorbs at high T
- Flyer mass is 1000 kg unloaded, 1500 kg loaded
  Wing area is 10 m^2, L / D = 5 / 1, $m_{CO}{}^2$ = 0.5 kg/sec
- Unlimited flight range
- Can land to investigate promising sites with instruments and recover samples (up to 100 kg.) Recharge stored CO_2 for flight to next site.

Figure 6.2.4

Illustrative Exploration Program for Xanadu

Manned Ice Rovers • 12 trips per year • 2 week trip time • ~10 locations explored per trip • Emplace 12 sub-surface mobile explorers (MICE) • Powered by on-board CH_4/O_2 • Total 1 ton CH_4 and 4 tons O_2 per year	**Unmanned Flyers** • ~50 trips per year • Ranges up to 10,000 km (i.e., as far as South Pole) • 2 weeks trip time • 2 to 3 locations explored per trip • Powered by compact nuclear reactor that heats atmospheric CO_2 for propulsion
Unmanned Flyers for Supply Depots • Lay supply depots for manned flyers (CH_4, O_2, consumables, etc.) • Depots laid at intervals of ~1000 km • ~5 to 10 flights per manned trip • Powered by compact nuclear reactor that heats atmosphere CO_2 for propulsion	**Manned Flyers** • 12 trips per year • Ranges up to 10,000 km (i.e., as far as South Pole) • 1 month trip time • 3 to 4 locations explored per trip • Powered by CH_4/O_2 combustion source heating atmospheric CO_2 for propulsion