ENGINEERING CONCEPTS FOR INFLATABLE MARS SURFACE GREENHOUSES

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LIST OF ACRONYMS

ALS	Advanced Life Support
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
BLSS	Biological Life Support Systems
BPC	Biomass Production Chamber
BVAD	Baseline Values and Assumptions Document
DART	Dust Accumulation and Repulsion Test
DRM	Design Reference Mission
ERV	Earth Return Vehicle
ESM	Equivalent System Mass
EVA	Extra Vehicular Activity
GCR	Galactic Cosmic Rays
HPS	High Pressure Sodium Lights
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JSC	Johnson Space Center
LAB	Laboratory Chamber
LEO	Low Earth Orbit
LMO	Low Mars Orbit
LPS	Low Pressure Sodium Lights
LSS	Life Support Systems
MAV	Mars Ascent Vehicle
MIP	Mars In-Situ-Propellant Production
MLI	Multi-Layer Insulation
PAR	Photo-Synthetically Active Radiation
P/C	Physico-Chemical

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1 Introduction

Comparing the early life of Mars and Earth, it seems both planets had much in common. Mars, in its early history, had a much denser atmosphere, higher temperatures and liquid water. Nowadays, the Mars atmosphere consists largely of carbon dioxide, with a typical surface pressure of about 0.01 Earth atmospheres, and a surface temperature that may reach 25° C on the equator in mid-summer, but which is generally much colder. At this pressure and temperature, water cannot exist in liquid form on the surface of Mars. The evidence of liquid water in the past, large riverbeds and ocean shore lines can be observed in many pictures of the surface of Mars. *What was the reason for the change of atmospheric conditions on Mars? Life started on Earth, could it have been started on Mars under similar conditions? Was there life on Mars?* Those are the questions that drove the interest in exploring Mars in the past. They may be answered by NASA's planned Mars exploration, defined by the Reference Mission. Regarding the decreasing resources, the increasing pollution and the high density of population on Earth, new questions have come up recently: *Can we change the harsh environment of Mars so that it is more habitable for humans?*, or more precisely formulated: *Could Mars have a biosphere once again?* [McKay, 1999]

There are many ideas of initiating a greenhouse effect on Mars in order to increase the low temperature and low pressure, but can it be done without negative side effects?

Maybe there was no LIFE on Mars …

©Pat Rowlings

... but there will be !!!

1.1 Mars Exploration: An Overview

In ancient Greece, the red planet personified the god of war "Ares". When the Romans conquered Greece, they adopted the symbol and named the planet for their god of war, "Mars". Through the middle ages astrologers studied the Mars motions to predict the future. Kepler discovered in 1609 that Mars orbits the Sun in an eclipse. Galileo first viewed Mars through his newly invented telescope. As telescopes improved, more of Mars could be seen: polar icecaps, color patterns on its surface, clouds and hazes. These observations all fit a habitable planet, and speculations that Mars was inhabited became more and more believable. [Exploring Mars, 1999]

NASA's Mars program consists of five major steps listed in table 1-1. The first step was sending a rover to the surface of Mars taking pictures and performing experiments in order to gather more information about the Martian environment. This was realized in 1997 when Pathfinder landed on Mars. Pictures of Ares Vallis, a giant channel, were taken. They showed a landscape with many rocks, some lined up in the direction that the flood waters flowed. Pathfinder carried a six-wheeled rover called Sojourner which explored the region around the lander. During its three months of activity, Pathfinder also measured temperatures and wind speeds on Mars and even recorded the passing of dust clouds over the landing site. In the future more information about the Martian soil will be gathered by returning a sample of a Martian rock to be analyzed on Earth. Designing a rocket that is able to return such a sample to Earth is still an important engineering challenge. A robotic outpost will be sent to Mars preparing the first human arrival. The strategy for the human exploration of Mars is described in NASA's Design Reference Mission, explained in section 2.1. The final step will be the permanent human settlement on Mars. The settlement of Mars presents new problems and challenges. Principal among these is the absence of a livable natural environment. [Exploring Mars, 1999]

Table 1-1: NASA's Mars Program [Exploring Mars, 1999]

STEP	MARS PROGRAM	YEAR
1	Rover	1997
2	Sample return	2008 +
3	Robotic outpost	2011 +
4	Human outpost	2014 +
5	Human settlement	?

1.2 Scope of this Thesis

NASA plans to launch a human exploration to Mars during the second decade of the new millennium. Resupply is prohibitive for these long duration Mars missions as it increases on the one side the launching mass and consequently the launching costs, on the other side the risks for the astronauts relying on frequent resupply from Earth. Regenerative life support systems will be used in order to provide self-sufficiency. Therefore, biological life support systems (BLSS) based on plant growth have to be developed and tested. One option is to grow plants in a Mars surface greenhouse not only as the primary source of food for the crew but also as the primary air and water regeneration processors.

During the studies for this document an Inflatable Mars Greenhouse Workshop was held on December 9 and 10, 1999, at Kennedy Space Center, Orlando, Florida. This workshop showed that studies about bioregenerative life support systems based on plant growth in greenhouses have begun to emerge recently. This workshop had a significant role in forming a framework for this research area. The workshop brought together scientists from various fields to exchange information about “Bioregenerative Life Support and Humans on Mars,” “Crop and Environment Interactions” and “Structural and Material Issues.” New technologies to solve occurring problems were discussed. One of the main points of the discussion was the possibility of huge mass savings by operating an inflatable greenhouse with an internal low pressure atmosphere and its impact on the plants. The feasibility of this concept is investigated in this document. At the end of this workshop all the identified issues for an inflatable Mars greenhouse were prioritized before a roadmap was created.

This document expands upon ideas obtained during the workshop and provides designs and engineering concepts for inflatable Mars surface greenhouses. It investigates the mass, power, cooling and crew-time requirements of a greenhouse operated at atmospheric pressure compared to a greenhouse operated at low pressure for three different lighting methods: natural, artificial and hybrid lighting.

Chapter 1 summarizes the history and future of the Mars exploration and provides the scope of this document. Chapter 2 introduces NASA’s reference mission and fundamental knowledge about the Mars environment. Chapter 3 gives an overview of important engineering considerations for inflatable Mars surface greenhouses. Life support systems, inflatable structures, thermal control system, lighting methods, operation and maintenance, equipment, interfaces, packaging and assembly, power sources are presented as well as possible in-situ resource utilization. In the section about life support systems the focus has been put on the integration and requirements of bioregenerative life support systems utilizing higher plants for food production. Background information about NASA’s BIO-Plex Project and studies on plant growth are summarized. Furthermore, TransHAB is explained as an example of the inflatable structure development at NASA. In Chapter 4 trade studies of the subsystems are conducted. These trade studies concentrate on the structure, material and thermal aspects of the greenhouse. Mass, power, cooling and crew-time requirements of high pressure greenhouses are compared to those of low pressure greenhouses by investigating the equivalent system mass of the different greenhouse design options. Risk analysis is used to determine the range and probabilities of the equivalent system mass results. Chapter 5 evaluates alternative design ideas for the greenhouse architecture. Chapter 6 describes the roadmap that has been developed at the workshop describing the further studies and experiments that have to be done until the final design of the greenhouse can be frozen for launch and transfer to Mars. Chapter 7 gives conclusions and recommendations for future investigations on Mars surface greenhouses. The greenhouse designs are compared by the design comparison evaluation.

2 Background

2.1 Design Reference Mission

The Design Reference Mission (DRM) is described in two publications: *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team* and its addendum *Reference Mission Version 3.0*. They provide a general framework for the human exploration of Mars, the strategy as well as a description of the systems.

Figure 2-1 illustrates the first mission sequence analyzed for the Reference Mission, which will be repeated three times. In this sequence, three vehicles will be launched from Earth to Mars. The first two launches in 2011 will not involve a crew but will send infrastructure elements to low Mars orbit (LMO) and onto the Martian surface. These two cargo missions will consist of an Earth return vehicle (ERV-1) and a lander. The ERV-1 aerocaptures into low Mars orbit and stays there until the first human crew leaves Mars to return to Earth. The lander will consist of an in-situ propellant production plant, power systems, an inflatable habitat and a Mars ascent vehicle (MAV). After the lander has been placed on the surface of Mars and the systems have been checked out the first human mission can be started. [Hoffmann et al., 1997; Drake, 1998]

In 2014 the first crew will be launched together with two additional cargo launches, consisting of ERV-2 and MAV-2, equal to the ones in 2011. These cargo launches take place to provide resources for the next human mission in 2016 and at the same time to provide redundancy for the present crew. If, for example, the ERV-1 or MAV-1 becomes inoperable the first crew can use the systems launched for the subsequent mission, ERV-2 and MAV-2, arriving approximately two months after the crew as the cargo will be sent on a minimum energy trajectory. If ERV-1 and MAV-1 operate as they are expected, then the ERV-2 and MAV-2 will support the second crew going to be launched in 2016. This sequence will be repeated in 2016 and 2018 (see figure 2-2). The Reference Mission can be extended by repeating the sequence. As a single Mars mission landing site is selected, infrastructure elements will be reused. This strategy allows to operate an inflatable Mars surface greenhouse for several years. [Hoffmann et al., 1997; Drake, 1998]

A 80-ton launch vehicle is required to place the mission elements into low Earth orbit (LEO). The crew will be launched on fast transfer trajectories, the transit time will be 130-180 days. During the transit they live in the transit habitat which will be used as descent vehicle and as primary habitat on the surface. The crew consists of 6 persons and the stay of the first expedition will be 537 Earth days which corresponds to 523.9 day-night cycles on Mars. The surface science concentrates on the search for life. Deep drilling, geology and microbiology investigations are supported by EVA and surface laboratories. The propellant production facility will autonomously produce the required 30 tones of oxygen and methane that will be used by the MAV to launch the crew to Mars orbit. There the crew will rendezvous with the ERV and return to Earth. As a fast transfer trajectory is chosen the crew will return to Earth after a transfer trip of 130-180 days descending to Earth by performing a precision parafoil landing. [Hoffmann et al., 1997; Drake, 1998]

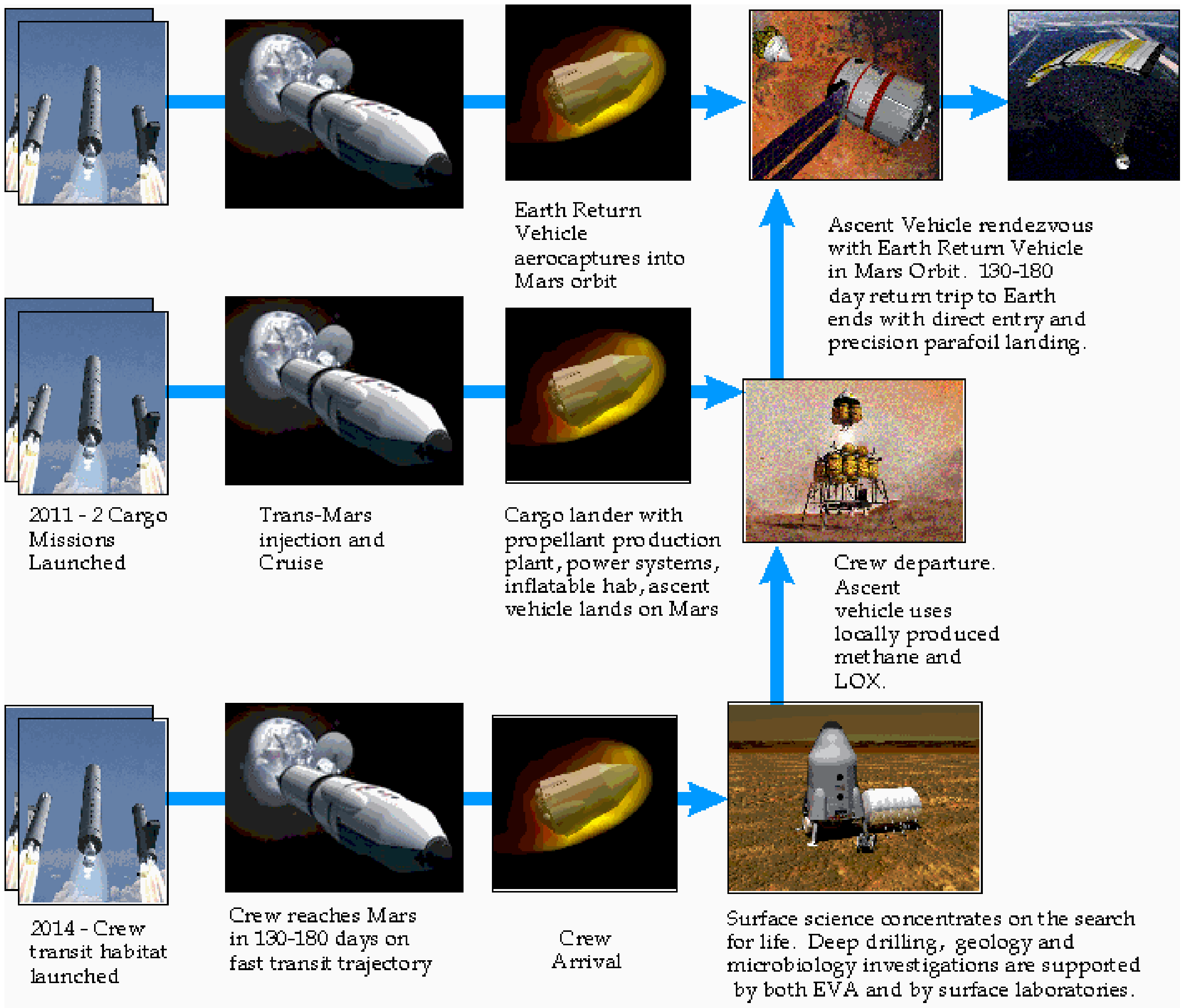


Figure 2-1: Reference Mission Sequence [Drake, 1998]

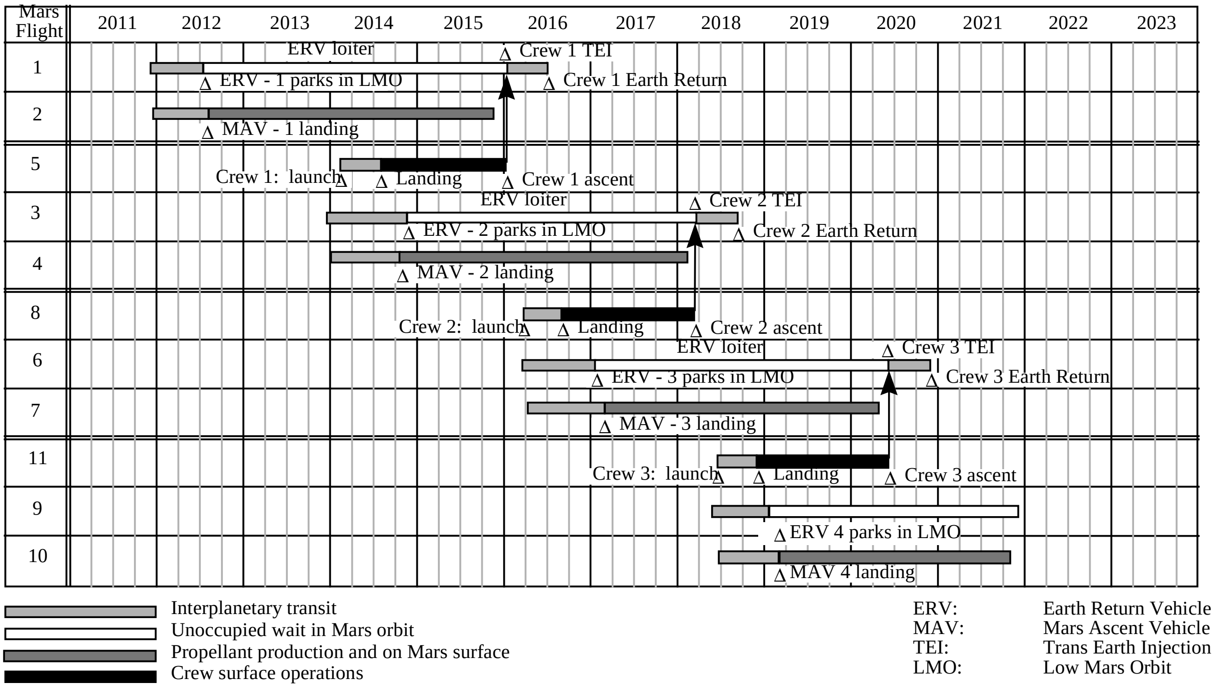


Figure 2-2: Timeline for the different Elements of DRM [Drake, 1998]

2.2 Mars Environment

Studies of Mars surface greenhouses require a good knowledge of the Martian atmospheric structure and dynamics, the Martian soil properties and the radiation on the surface. Atmospheric pressure is of great importance since the structure of the greenhouse depends on the pressure on its surface. Dust and cloud particles suspended in the atmosphere can impact and damage the surface of the greenhouse, reduce the effectiveness of solar power generation systems and decrease the irradiance of sunlight inside the greenhouse. Atmospheric winds become an important design criteria since they affect the design of the greenhouse's shape and the possible location of the greenhouse on the planet's surface. On the other hand, the atmosphere and the soil of Mars have to be studied in order to find resources for the life support systems; for example, gaseous elements of the Martian atmosphere, water in the atmosphere or as ice/permafrost on/under the planet's surface, and workable surface material. The radiation on the surface of Mars has to be accurately measured in order to include the necessary shielding in the greenhouse structure for both the plants and the crew. [Viking Mission to Mars]

Several missions were designed in order to measure the environment of Mars, among them NASA's Viking Mission (see table 2-1). The primary mission objectives of the Viking Mission to Mars were to obtain high resolution images of the Martian surface, characterize the structure and composition of the atmosphere and surface, and search for evidence of life. The Viking Mission was composed of two spacecraft, Viking 1 and Viking 2, that touched down on Mars in July and September 1976. [Viking Mission to Mars]

Table 2-1: NASA's Missions to Mars [Chronology of Mars Exploration]

MISSION EVENT	DATE
Mariner 4 flyby	January, 1961
Mariner 6 flyby	July, 1969
Mariner 7 flyby	August, 1969
Mariner 9 arrival in orbit	November, 1971
Viking 1 landing	July, 1976
Viking 2 landing	September, 1976
Mars Observer disappears	August, 1993
Mars Pathfinder landing	July, 1997
Mars Global Surveyor arrival in orbit	September, 1997
Mars Climate Orbiter disappears	September, 1999
Mars Polar Lander disappears	December, 1999

The orbit of Mars around the sun lasts for 687 Earth days. The mean solar day of Mars is nearly the same as the one of Earth (24 hours 39.35 min). The surface gravity is almost 40% of Earth's (see table 2-2). [Mars Fact Sheet]

2.2.1 Atmosphere

The Mars atmosphere is highly variable on a daily, seasonal and annual basis. The thinness of the atmosphere and solar heating (which is 44% of terrestrial values) guarantees a large daily temperature range at the surface under clear conditions. On an annual basis, the atmospheric pressure at the surface changed from 6.9 to 9 mbar at Viking 1 lander site due to condensation

and sublimation of CO_2. The mean atmospheric pressure is estimated at 6.1 mbar. [Kaplan, 1988]
Although Mars has no liquid water and its atmospheric pressure is approximately 1.0 percent that of Earth, nonetheless many of its meteorological features are similar to the terrestrial ones. Water ice clouds, fronts with wind shifts and associated temperature changes similar in nature to those on Earth can be found. The main differences between the Earth and the Mars atmosphere are that the Mars atmosphere does not transfer as much heat as the Earth atmosphere, and it cools much faster by radiation. Mars diurnal temperature cycle is larger than Earth's (184 to 242 K during the summer, but stabilized near 150 K (CO_2 frost point) during the winter). Water ice clouds occur due to many different causes just as on Earth. Nighttime radiation cooling produces fogs; afternoon heating causes drafts which cool the air and cause condensation; flow over topography causes gravity clouds; and cooling in the winter polar regions causes clouds. [Kaplan, 1988]

The solar irradiance varies in function of season, latitude, time of day and optical depth of the atmosphere. The solar irradiance incident on the surface of Mars consists of two components: the direct beam and the fuse component. The fuse component comprises the scattering by small particles in the atmosphere and the diffuse skylight. The solar radiation on Mars varies according to the ellipticity of the Mars orbit. The mean solar radiation on Mars is 589 W/m^2. The ultraviolet radiation, which reaches the Mars surface is much greater than on Earth, because the Martian atmosphere is more tenuous. The ultraviolet radiation is mainly absorbed by carbon dioxide, all ultraviolet radiation with a wavelength minor than 200 nm is absorbed by the atmosphere. [Kaplan, 1988]

In table 2-2 the Mars environment properties are summarized. Table 2-3 describes the composition of the atmosphere of Mars in terms of the gases present and their mole fraction. [Mars Fact Sheet; Kaplan, 1988]

Table 2-2: Environment Properties [Mars Fact Sheet; Kaplan, 1988; Charr, 1981]

PROPERTY	VALUE-MARS	VALUE-EARTH
Orbit period	687 days	365 days
Rotation period	24.62 hours	23.93 hours
Gravity	3.69 m/s^2	9.78 m/s^2
Surface pressure	~6.1 mbar (variable) 6.9 mbar to 9 mbar (Viking 1 Lander site)	1014 mbar
Surface density	~0.020 kg/m^3	1.217 kg/m^3
Average temperature	~210 K	288 K
Diurnal temperature range	184 - 242 K (summer) 150 K (winter)	283 - 293 K
Wind speeds	2- 7 m/s (summer) 5-10 m/s (fall) 17-30 m/s (dust storm)	0-100 m/s
Solar irradiance	589 W/m^2	1368 W/m^2
Drifting material Size Cohesion	 0.1-10 μm 1.6±1.2 kPa	

Table 2-3: Composition of the Atmosphere of Mars [Mars Fact Sheet; Kaplan, 1988]

GAS	MOLE FRACTION
CO_2	0.955 ± 0.0065
N_2	0.027 ± 0.003
Ar	0.016 ± 0.003
O_2	0.0015 ± 0.005
CO	0.0007
H_2O	210 ppm
NO	100 ppm
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm

Mars has local dust storms of at least a few hundred kilometers in extent. The duration and extent of Martian dust storms vary greatly. Dust storms of planetary scale may occur each Martian year with a velocity of up to 30 m/s. Unfortunately, neither Earth based nor spacecraft observations have been systematic enough to quantify the frequency of dust storm occurrence or even the true extent of many individual storms. There is no reliable method for prediction of great dust storms. They mainly occur during southern spring and summer. Local dust storms have been observed on Mars during all seasons, but they are most likely to occur during the same periods as the great dust storms. The physical grain size of the drifting material may be estimated to be 0.1 to 10 μm. It has the characteristics of very fine grained, porous materials with low cohesion. [Kaplan, 1988]

The dust raised into the atmosphere by dust storms and the ordinary atmospheric dust always present in the atmosphere settles out the atmosphere onto any horizontal surface. Measurements made by the Pathfinder Mission showed a 0.3% loss of solar array performance per day due to dust obscuration. This dust deposition could be a significant problem for a greenhouse operated with solar light for long duration missions, unless a technique is developed to remove the dust periodically or prevent settled dust from coating the greenhouse surface (see section 3.5.3). The dust affects both the intensity and the spectral content of the sunlight. The solar irradiance on the surface of Mars during a global dust storm is comparable to the one of a cloudy day on Earth (see table 2-4). [Kaplan et al., 1999]

Table 2-4: Average Solar Intensity of Mars compared to Earth [Clawson et al., 1999]

LOCATION	TOTAL SOLAR INTENSITY [W/m^2]	RELATIVE SOLAR INTENSITY [%]
Earth Orbit	1368	100.0
Earth Surface (Clear)	774	56.6
Earth Surface (Cloudy)	78	5.7
Mars Orbit	589	43.0
Mars Surface (Clear)	301	22.0
Mars Surface (Cloudy-Local Storm)	178	13.0
Mars Surface (Cloudy-Global Storm)	89	6.5

Summarizing the impacts of the Martian atmosphere on the design of the greenhouse, the low Martian atmosphere pressure of 6 mbar is considered to be the major obstacle. The temperature is relatively easy to support. As the 60 kPa pressure (surface habit pressure, see section 3.1.5.3.1) inside the greenhouse leads to a huge pressure difference on the surface of the greenhouse, the structure has to be strong enough to maintain those loads. This problem could be solved by growing the plants in a low pressure greenhouse. The feasibility of this concept is investigated in this document. [McKay, 1999]

2.2.2 Soil Properties

The mean density of Martian soil is 1.0-1.8 g/cm^3. The regolith compositions are modeled using the mass-normalized concentrations of the five most abundant elements in the soil. The composition of the Martian regolith based on Viking mission data is given in table 2-5. The regolith could be used as shielding material (see section 2.2.3). Another possible option of using in-situ resources is the consideration of growing plants on Martian regolith. As the Martian soil has not been analyzed sufficiently it cannot be decided if it provides adequate nutrients needed for plant growth. The greenhouse studies in this document are based on the implementation of a hydroponic culture (see section 3.1.5.2). [Wilson et al, 1997]

Table 2-5: Composition of Martian Regolith [Wilson et al., 1997]

COMPOSITION	MASS PERCENTAGE
SiO_2	58.2%
Fe_2O_3	32.7%
MgO	10.8%
CaO	7.3%

2.2.3 Radiation on the Surface

The most critical aspect of manned Mars exploration is the safety and health of the crew. One of the major health concerns are the damaging effects of ionizing space radiation. If a greenhouse with a pressure of 60 kPa (surface habit pressure, see section 3.1.5.3.1) is chosen, the crew enters the greenhouse without space suits, i.e. without personal radiation protection. Consequently, the greenhouse has to provide the necessary shielding against the hazardous radiation environment of Mars for both humans and plants. If the greenhouse is operated at a very low pressure, i.e. the astronauts enter the greenhouse with space suits, the amount of radiation protection depends mainly on the plants. Plants show lower radiation sensitivity than humans. Table 2-6 demonstrates that the radiation dose that produces observable effects is much higher for plants (e.g. ~3.77 Sv for onions) than for humans (~0.25 Sv). Lethal doses for plants (e.g. ~14.91 Sv for onions) are also higher than for humans (~4.50 Sv). Consequently, the shielding for a low pressure greenhouse with a high level of automation and mechanization would be minimal compared to a human rated facility. [Wilson et al., 1997]

For the surface analysis considerations, radiation doses from galactic cosmic rays (GCR) and solar proton flares are of the most concern. The natural radiation environment on Mars varies according to the solar activity. The solar dipole moment cycles approximately every 20-24 years leading to solar activity cycles of 10-12 years modulated by the direction of the dipole moment. The solar activity increases with the decline of the dipole moment with maximum activity occurring as the dipole switches hemispheres. Activity declines as the dipole moment maximizes along its new direction. With each activity cycle there are approximately 3 ½ to 4 years of active solar conditions. The greatest possibility of a large solar proton event is during the rise and decline in solar activity. The magnitude of the GCR fluxes varies over the 10-12 year solar cycle. The fluxes are greatest during solar minimum conditions when the interplanetary magnetic field is the weakest, allowing more intergalactic charged particles to gain access to our solar system. During maximum solar activity, the GCR fluxes are in their minimum, however, the probability of a large solar proton event increases significantly. [Wilson et al., 1997]

The constant bombardment of high-energy particles deliver a lower steady dose rate compared with large solar proton flares which can deliver a very high dose in a short period of time (on the order of hours to days). GCR contribution to dose becomes more significant as the mission duration increases. For the long duration missions, the GCR can become career limiting. In addition, the biological effectiveness of the GCR high-energy and high-charge particles are not well understood and lead to uncertainties in the biological risk estimates. The amount of shielding required to protect the astronauts will depend on the duration of the mission and the time and frequency the astronauts have to enter the greenhouse for servicing and eventually harvesting. [Wilson et al., 1997]

Solar proton flares are also a radiation hazard for crew members on the Martian surface. Very large solar proton events are relatively rare with one or two events per solar cycle. A solar flare event can be very dangerous if a habitat is inadequately shielded because of its potentially high dose. The amount of shielding required for protection will depend on the nature of the energy spectrum and the intensity of the event. [Wilson et al., 1997]

Although Mars is devoid of an intrinsic magnetic field strong enough to deflect charged particles, it does have a carbon dioxide atmosphere, which will help protecting surface crews from free space radiation fluxes. Shielding materials can possibly be provided without excessive launch weight requirements from Earth by utilizing local resources such as Martian regolith (see section 2.2.2). One configuration is to have a various thickness of Martian regolith surrounding the greenhouse, while another configuration assumes the greenhouse located next to a high cliff. [Wilson et al., 1997]

Table 2-6: Possible Ranges for Effects of Ionizing Radiation on Selected Plants [Clawson et al., 1999]

ORGANISM	OBSERVABLE EFFECTS	LETHAL DOSE
Human (Annual limit < 0.05 Sv)	~0.25 Sv	~4.50 Sv
Onion	~3.77 Sv	~14.91 Sv
Wheat	~10.17 Sv	~40.22 Sv
Corn	~10.61 Sv	~41.97 Sv
Potato	~31.87 Sv	~126.08 Sv
Rice	~49.74 Sv	~196.77 Sv
Kidney Beans	~91.37 Sv	~361.49 Sv
Potential Dose: Solar Maximum: ~0.40 Sv Solar Maximum: ~1.20 Sv Solar Flare: ~5.00 Sv		

3 Systems and Elements of an Inflatable Mars Surface Greenhouse

3.1 Life Support Systems

3.1.1 Life Support Requirements on Planet Mars

Life support represents the most critical technology needed for a successful and safe manned mission to Mars. The life of the astronauts depends on a complex mix of biological and engineering systems. It has to provide the air they breathe, the water they drink and the food they consume (see figure 3-1). Such Life Support Systems (LSS) will be developed and tested on the International Space Station (ISS). LSS for the ISS will be constrained to minimize mass and volume requirements and are designed for microgravity conditions. [Reiber, 1988]

The situation is different on Mars. With a gravity almost 40% of Earth's and in-situ resources available for producing a wide range of needed materials, the Mars environment makes possible a LSS which can support a more adaptive, dynamic and aggressive effort. Table 3-1 summarizes the life support criteria of the space environment vs. the Mars environment. [Reiber, 1988]

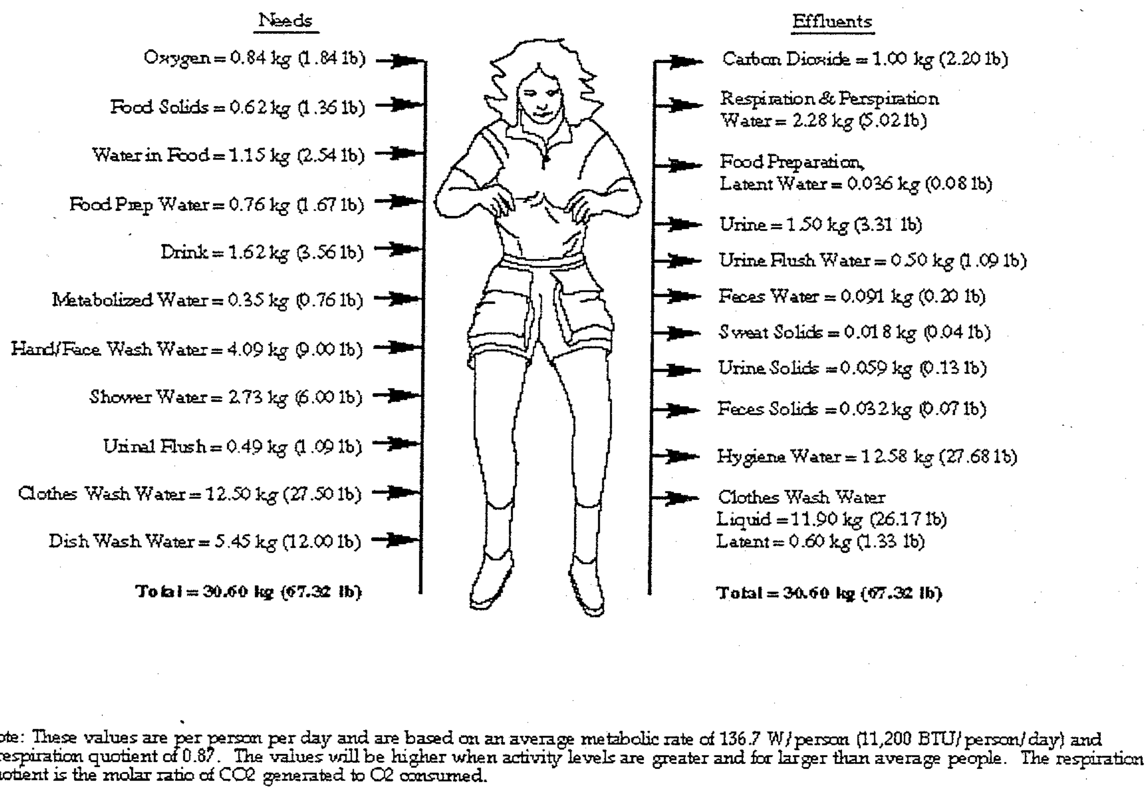


Figure 3-1: Human Metabolism [NASA, 1996]

Table 3-1: Life Support Criteria: Space Vs. Mars Environment [Reiber, 1988]

MICROGRAVITY ENVIRONMENT	MARS ENVIRONMENT
High degree of closure of water/breathable gas	Water and gas available on Mars
Low mass, low volume	Low mass, large volume augmentable
Food transported	Food grown in-situ
Solid waste stored	Solid waste recycled
Microgravity environment	Fractional gravity (3/8 g)

3.1.2 Advanced Life Support

The goal of NASA's Advanced Life Support Program (ALS) is to provide self-sufficiency in life support for productive research and exploration in space, benefits on Earth, and to provide a basis for planetary explorations. [Lange et al., 1998]

For long-duration missions open loop life support systems have to be replaced by closed loop life support systems, in order to avoid the high costs associated with the launch and storage of consumables and high risk of relying on frequent resupply missions. Gradually the loops for water, CO_2, O_2, N_2 and finally food will have to be closed. The approximate reduction of relative resupply mass by loop closure is shown in table 3-2. [Eckart, 1996]

Table 3-2: Reduction of Relative Resupply Mass by Loop Closure [Eckart, 1996]

STEP	METHOD	RELATIVE SUPPLY MASS
0	Open loop	100%
1	Waste water recycling	45%
2	Regenerative carbon dioxide-absorption	30%
3	Oxygen recycling from carbon dioxide	20%
4	Food production from recycled wastes	10%
5	Elimination of leakage	5%

In contrast to the life support systems (LSS) for the current short-duration missions biological processes in addition to physico-chemical (P/C) processes, such as food production utilizing higher plants will be implemented for long-duration missions. According to table 3-2 the relative resupply can be reduced to 10% when the food loop is closed compared to an open loop system, where all consumables are brought from Earth. Valuable chemicals will be recovered by processing solid waste. In-situ resources, where available, may also be used to replenish life support consumables. [Eckart, 1996]

The objectives of the Advanced Life Support Program are to: [Lange et al., 1998]

- Recycle air, water, food and waste.
- Minimize required involvement of the crew in life support operations.
- Provide environmental control and monitoring.
- Provide thermal control.
- Assure prolonged reliability of components and systems.
- Provide in-situ maintenance.
- Minimize the impact of life support on planetary environments.

The growth of higher plants can not only serve for food production, but also for atmosphere revitalization and water regeneration as the photosynthesis process transforms carbon dioxide in oxygen and water can be cleaned by plant transpiration. If more than about 25% of the food is produced locally, all the required water can be regenerated. If approximately 50% of the required food is produced locally the required air can be completely regenerated. [Drysdale et al., 1999]

The requirements for a food production system are to: [Lange et al., 1998]

- Produce food that meets human requirements for nutrition, sensory acceptability and food safety.
- Provide the environmental and cultural requirements to produce crop, including the atmosphere temperature and composition, the lighting intensity and spectral composition, the growth area, the volume and root zone.
- Provide post-harvest processing, materials handling and storage of harvested products.
- Utilize resources recovered from other life support systems, including carbon dioxide, waste water and solid wastes.
- Provide non-food products to other life support systems for utilization, further processing or disposal, including oxygen, transpired water, heat and inedible biomass.

The advantages and disadvantages of using a greenhouse for in-situ food production instead of bringing food from Earth by resupply missions are given in table 3-3.

Table 3-3: Advantages and Disadvantages of Utilizing In-situ Food Production

ADVANTAGES	DISADVANTAGES
- Self-sufficiency - Provision of fresh food - Reduction of resupply mass - Reduction of risk by relying on frequent resupply missions - Regeneration of air - Regeneration of water - Positive psychological effect for crew entering the greenhouse - Crew can live in greenhouse for a certain amount of time in case of fire in habitat	- High initial mass - High power and volume requirements - High crew-time requirements for operation and maintenance - Unknown reliability - Insufficient test data of plants, concerning atmosphere and gravity requirements - Single site mission scenario or permanent Martian base required

3.1.3 BIO-Plex Project

Advanced life support systems are based on the integration of regenerative biological and physicochemical (P/C) processes to produce food, potable water, and a breathable atmosphere from metabolic wastes. A large-scale human-rated test facility, the Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex), is under development at the NASA Johnson Space Center. It will be used to acquire the information and operational experience necessary to define performance and design requirements for advanced life support systems needed to sustain the crew on long duration space missions. [Tri, 1999]

The BIO-Plex is being designed as an interconnected multi-chamber test bed, consisting of five major chambers (a habitation chamber, a life support systems chamber, a laboratory chamber (LAB) and two biomass production chambers [BPC 1 and BPC 2]) joined by an interconnecting tunnel, with access to the test bed through an air lock (see figure 3-2). All chambers are cylindrical and sized to fit in the space shuttle cargo bay. The BIO-Plex comprises a series of facility test support systems, life support systems, a human accommodations system and science and technology support accommodations. The life support systems consist of combinations of biological and physicochemical processes to test functions such as the air revitalization system, the biomass production chamber, the food processing system, the integrated control system, the solids processing system, the thermal control system and the water recovery system. The relationships between the biomass production chamber and other life support systems are depicted in figure 3-3. [Tri, 1999]

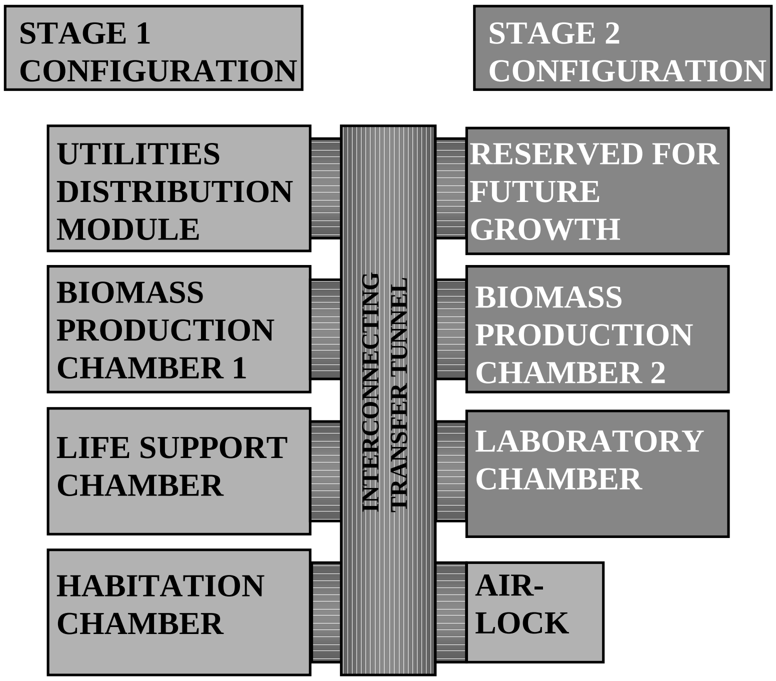


Figure 3-2: Configuration of BIO-Plex [Tri, 1999]

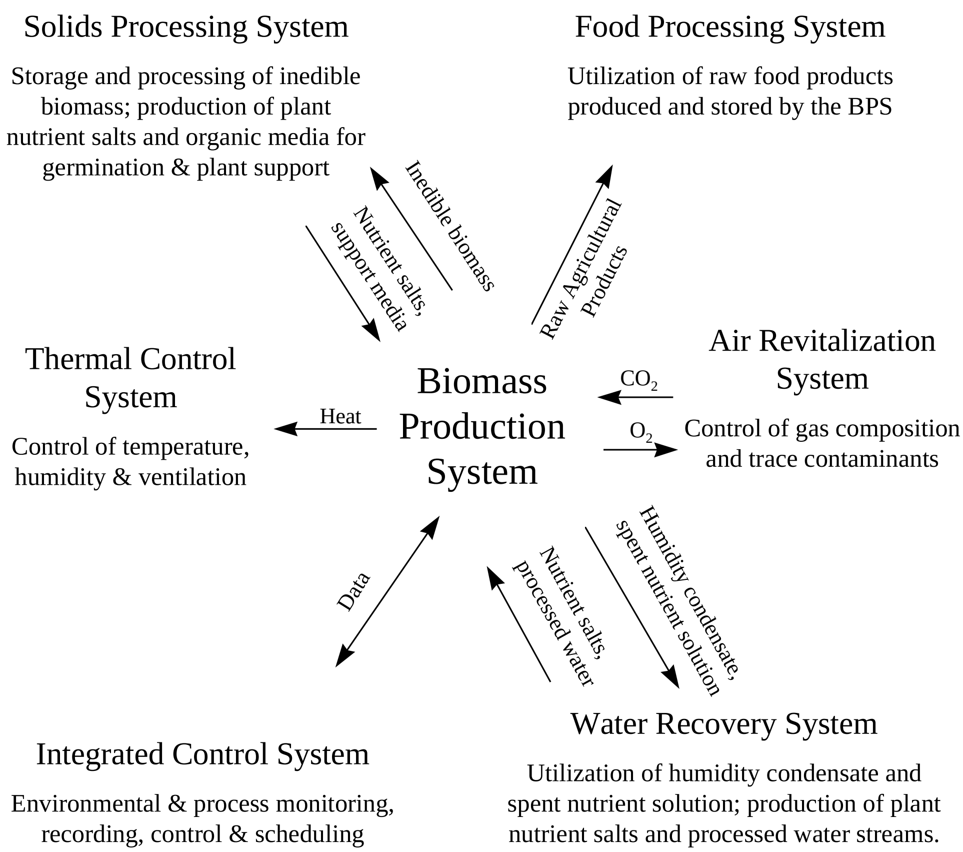


Figure 3-3: Interfaces, Mass and Energy Flow between the Biomass Production System and other Life Support Systems within the Bio-Plex [Tri, 1999]

Four major tests are scheduled for the BIO-Plex, with increasing duration of the test. For the first test the human crew will spend 120 days in the stage 1 configuration, i.e. only BPC 1 will be operated. The crew air and crew water loops will be separated from the plant air and water loop. A ”hot” start without transition will be used, i.e. the plants will be at full maturity from the very beginning, stored agricultural products ready for processing are provided, the biological water and the biological waste processor are fully inoculated at steady stage and also the heat load and the control and monitoring are at steady stage. The biological system used from the very beginning is primary the air processor with or without P/C gas separation. For the second test some transition from P/C biological processes will be performed. The plant air loop will still be separate from the crew air loop, but the plants are used as partial water processor. This test and the third test will last for 240 days. The third test will be performed in the stage 2 configuration, i.e. BPC 2 and the LAB will be added to the test facility. The plants will be used as a significant water processor and a partial air processor. The forth test is foreseen as a 540-day truly autonomous operation with full transition using P/C systems during the startup and integrating biological systems gradually. Instead of plants at full maturity only seeds will be provided. An overview of the four tests is depicted in figure 3-4. The BIO-Plex project long-range schedule can be found in figure 3-5. [Tri, 1999]

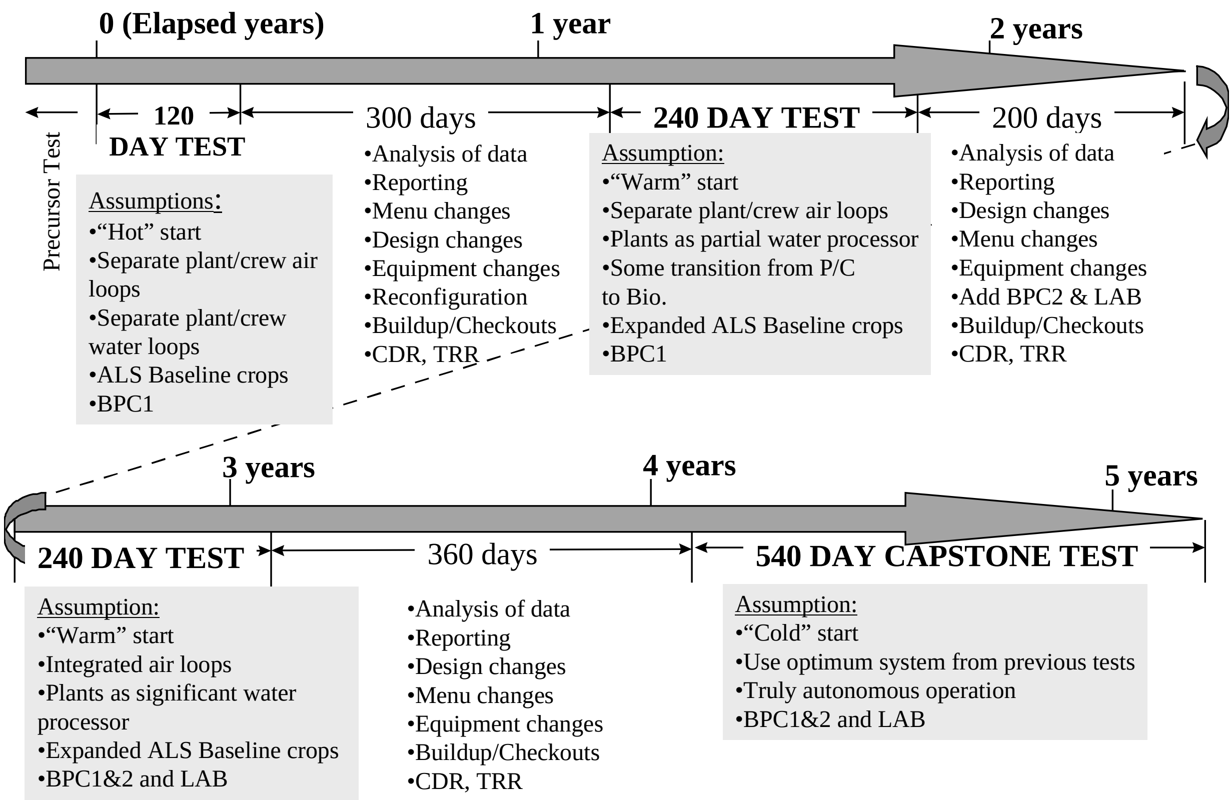


Figure 3-4: BIO-Plex Human Testing Timeline [Tri, 1999]

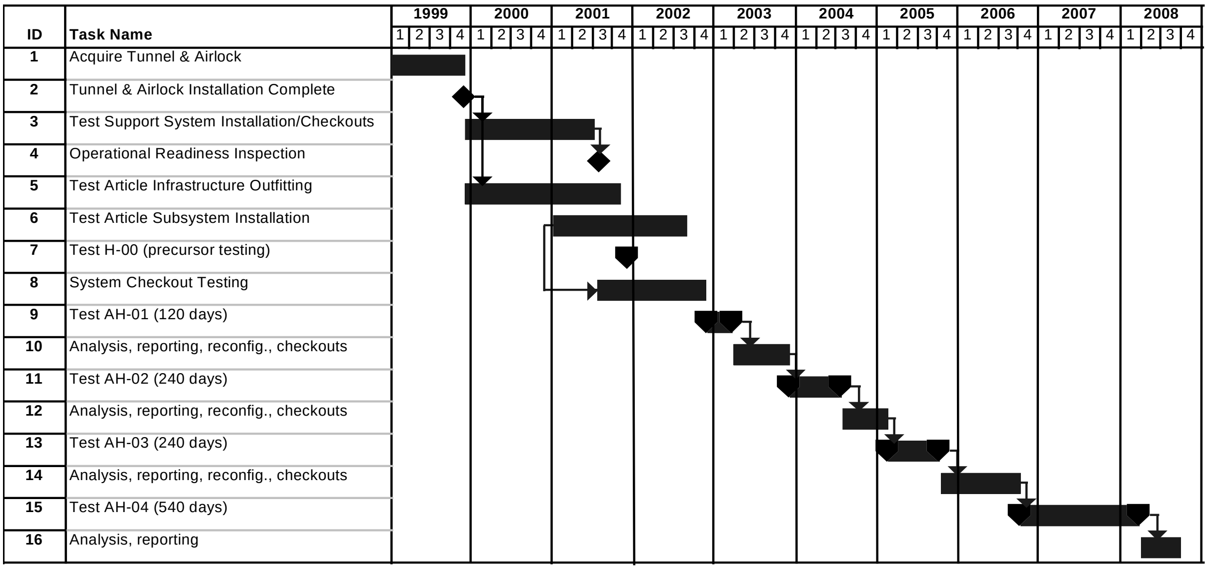


Figure 3-5: BIO-Plex Project Long-Range Schedule [Tri, 1999]

The last test is expected to be finished in 2008. The data and especially the operational experience gained from the Bio-Plex project will contribute to the Mars greenhouse design process. Currently, most of the available data is based on growth chamber experiments. A growth chamber usually is very small, self-contained and tends to be dedicated to a specific crop at one time. It provides the plants necessary nutrients, air, water and light but does not have to be a human-rated pressure vessel. Therefore, it does not have to meet the verification, reliability or failure redundancy as it would if it were human-rated. A greenhouse on the other hand is a larger facility, which a human can enter in order to tend a larger variety of crops on a larger production scale.

3.1.4 Selection of Plants

The plants grown in the greenhouse must be able to provide a nutritionally and psychologically satisfactory diet for the crew in order to keep them healthy and motivated. It is important that the diet meets the psychological requirements of the humans, regarding the variety and contrast of crops. Another selection criteria would be the time and costs that are involved in food preparation labor and waste processing. As the growth area of a greenhouse is limited, highly productive plants have to be selected. Moreover, the atmosphere, water and waste regeneration capability of the plants have to be considered. Further requirements include fast growth, high harvest index, growth on low-quality water and a high transpiration rate. If, for example, 5% of the required plants are grown locally the human psychology drives the selection. The goal would be to maximize the contrast with prepackaged food by providing “fresh” textures, colors, flavors and aromas. Salad vegetables would be selected to fulfill these requirements. If, for example, more than 85% of the required food is grown locally the life support system would approach self-sufficiency. Only meat, spices and other ingredients would be brought from Earth, as their local production is expected to be not feasible. [Drysdale et al., 1999; Hunter, 1999]

The results of the BIO-Plex test (see section 3.1.3) will contribute to an appropriate selection. Nevertheless, the behavior of the plants under fractional gravity is not considered in the BIO-Plex tests. Tests on the International Space Station have to evaluate the impacts of gravity on

plants. The plants considered to be useable for advanced life support purposes are: [Drysdale et al., 1999; Hunter, 1999]
Soybean, wheat, white potato, sweet potato, rice, peanut, tomato, carrot, cabbage, lettuce, dry bean, celery, green onion, strawberry, peppers, pea, mushroom, snap bean, spinach.

3.1.5 Requirements of Plants

3.1.5.1 Growth Area

The crop production is based on the **photosynthesis process** where, as a first step, radiative energy of the sun is trapped and transformed into chemical energy. This chemical energy subsequently is used to reduce CO_2 molecules and to form the essential building blocks: sugars, amino acids and energy for growth and maintenance of the crop. The building blocks are transported to the growing centers in the plant, together with water and nutrients that are used for growth of cells and organs. The chemical equation for the photosynthesis process of plants is the following: [Hashimoto et al., 1993]

$$6\ CO_2 + 12\ H_2O + \text{light} \Rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

A preliminary study defines the relationship between the amount of edible plant mass that would be grown and the amount of **natural light** available as: [Gertner, 1999]

$$\text{Edible} = 0.77 \times PAR \times \tau - 6.1$$

where:

Edible = amount of edible plant mass produced (g/[m^2 x day])
PAR = lighting level of photo-synthetically active radiation (PAR) on Mars (20.8 mol/[m^2 x day])
τ = transmittance of greenhouse surface (assumed to be 0.55/0.65 for a high/low pressure greenhouse)

The actual amount of PAR depends on the local weather conditions and changes throughout the Martian season. The average daily PAR on Mars was calculated at 20.8 mol/(m^2 x day). The transmittance of the greenhouse is assumed to be 0.55 for a greenhouse operated with high pressure (60 kPa) and 0.65 for a greenhouse operated at low pressure (30 kPa) (see section 3.4). [Gertner, 1999]

If **artificial light** is used:

τ = 1
PAR = lighting level of photo-synthetically active radiation of the lamps (mol/[m^2 x day])

According to section 3.1.1 the crew needs 1.77 kg food/(crew x day). If 55% of the diet is grown on Mars, 0.97 kg food/(crew x day) have to be produced. Assuming 6 crew members and crew needs of 0.97 kg food/(crew x day), the total amount of food needed in a Martian year (686.5 Earth days) is 3995.4 kg. The **total growth area** is determined by dividing the total amount of food needed by the amount of edible plant mass produced: [Gertner, 1999]

Area = Food / Edible

where:

Area = growth area (m^2)
Food = amount of food needed for crew (3995.4 kg/Martian year)
Edible = amount of edible plant mass produced (g/[m^2 x day])

Consequently, a growth area of 2150/1351 m^2 would be needed to support a crew of six people using a high/low pressure transparent greenhouse with exclusively natural light. Assuming greenhouses with a growth area of 90 m^2, 24/15 greenhouses would be needed. Artificial light may help to reduce the growth area significantly. Assuming an artificial lighting level of 1000 μmol/(m^2s), a growth area of 215 m^2, i.e., 3 greenhouses providing a growth area of 90 m^2 would be required. The value for the required growth area for the hybrid greenhouse is in-between the values for natural and artificial lighting, as hybrid lighting is a combination of those lighting methods (see figure 3-6). [Gertner, 1999]

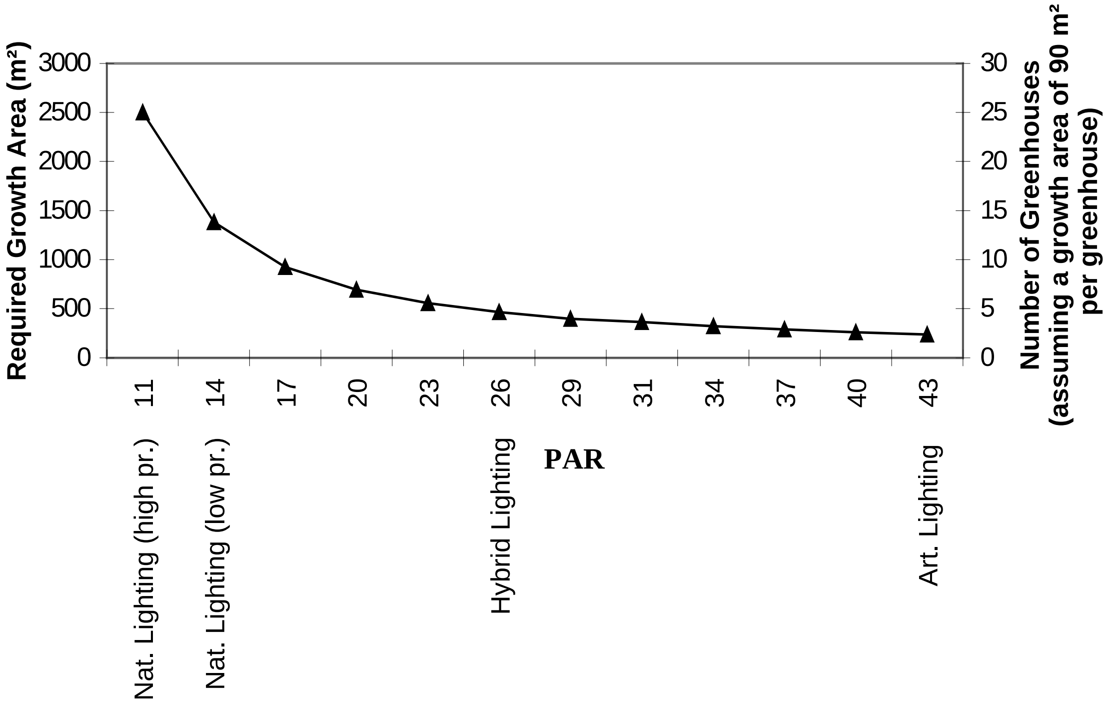


Figure 3-6: Relation of Lighting Method, Growth Area and Number of Greenhouses

3.1.5.2 Growth Media

One important factor of the plant growth system is the growth media. The selection of an appropriate growth method depends on the selected plant species. Growth media options, with and without substrate, include: [Eckart, 1996]

- Soil, brought from Earth
- Martian regolith
- Hydroponics
- Aeroponics

- Zeoponics

Soil, brought from Earth, may not be attractive as a natural resource due to transportation costs, potential problems of microbiological contamination and the handling difficulties introduced during planting and harvesting. [Eckart, 1996]

An option of using in-situ resources may be the consideration of growing plants on Martian regolith. As the Martian soil has not been analyzed sufficiently it cannot be decided if it provides adequate nutrients needed for plant growth (see section 2.2.2).

Plants do not necessarily need solid root media. Plant growth can be assisted by structural support. Nevertheless, a nutrient solution has to be supplied to the plants. The two existing methods for plant growth in extraterrestrial environments are hydroponics and aeroponics. In hydroponic systems, plants are grown with their roots in an aerated, circulating nutrient solution that provides nutrients, oxygen and water. An advantage of liquid nutrient solutions over solid substrates is that much of the nutrient can be recovered and reused as well as the water. A disadvantage of hydroponic systems is the reduced oxygen uptake in plant roots at low oxygen partial pressures. The liquid solution provides a thicker boundary layer and consequently requires a greater difference in oxygen partial pressure to maintain a diffuse flux of oxygen to the root for consumption during respiration. Furthermore, hydroponic systems require careful monitoring and frequent maintenance. [Eckart, 1996; Lacey, 1999]

In aeroponic systems, the nutrient solution is supplied to substrate-free plant roots by sprayers in the form of fog. An advantage of areoponic culture is the small amount of nutrient solution per unit of growth area resulting in a huge mass reduction of the cultivation devices. On the other hand, the decrease in volume of the nutrient solution has the disadvantage of more rapid accumulation of toxic products than when plants are grown on an unchanging medium. The aeroponic system needs frequent monitoring and adjustment to maintain a desirable salt balance and solution pH. [Eckart, 1996]

Hydroponic and aeroponic nutrient delivery systems are complex and require pumps and sophisticated control and monitoring equipment. Zeoponics have been developed to simplify plant growth. Zeoponic plant growth is the cultivation of plants in zeolite mineral substrates that contain essential plant growth nutrients. These plant growth nutrients are released slowly into the solution and are available for the plant growth. The zeoponic system does not necessarily need sophisticated monitoring and control systems. [Eckart, 1996]

Comparing the different methods of plant cultivation, the hydroponic system may be the most suitable for application in an inflatable Mars greenhouse. High productivity rates have been achieved with hydroponic systems and in contrast to the relatively new zeoponic system much experience is available. Nevertheless, the Martian regolith should be analyzed and considered, as a solid medium is preferable for low pressure plant growth since it provides a better oxygen uptake in the plant roots. [Eckart, 1996; Lacey, 1999]

3.1.5.3 Atmosphere Requirements

3.1.5.3.1 Pressure and Composition

This document compares the feasibility of a 60 kPa pressure greenhouse to a low pressure greenhouse. For these two types of greenhouses different gas compositions depending on the plant and human requirements are necessary.

- **60 kPa pressure greenhouse (surface habitat pressure)**
  A greenhouse providing a 60 kPa pressure with a gas composition equal to the one of the surface habitat has several advantages. The air exchange between the surface habitat and the greenhouse can be simplified if both modules consist of the same atmosphere composition and pressure. Furthermore, the humans entering the greenhouse do not need a space suit and no pre-breathing is required. Humans can do the servicing and harvesting while the low level of automation and mechanization leads to energy and mass savings.
  The atmosphere of a greenhouse of 60 kPa pressure has to provide a habitable environment for the crew and therefore it is based on human physiological needs listed in table 3-4. The atmosphere composition of the surface habitat is shown in table 3-5.

Table 3-4: Physiological Constraints for Habitable Environments [Drysdale et al., 1999]

ATMOSPHERE PARAMETER	LOWER LEVEL	UPPER LEVEL
Total Pressure	59.2 kPa	101.3 kPa
Oxygen Pressure	17.76 kPa	23.1 kPa
Carbon dioxide Pressure	0.031 kPa	0.71 kPa
Relative Humidity	25%	75%
Temperature	18.5 °C	26.8 °C

Table 3-5: Atmosphere Composition of the Surface Habitat [Drake, 2000]

GAS	PRESSURE
O_2	17.8 kPa
N_2	39.0 kPa
H_2O	2.0 kPa
CO_2	0.4 kPa
Total pressure	59.2 kPa

- **Low pressure greenhouse**
  A way to save on structural mass and reduce the leakage rate would be an inflatable greenhouse operated with **low pressure**. Plant responses to low pressure have been studied for the last ten years. Lately, studies on very low pressure responses have been performed. At a total pressure of 0.3 atm (~30 kPa) plant growth is still possible, 0.2 atm (~21 kPa) is considered to be the limit. A pressure of 0.3 atm is equal to the air pressure on the top peaks of the world in the Himalayas. [Henninger, 1999; Wheeler, 1999]

  The essential gases for a greenhouse atmosphere are O_2, CO_2 and H_2O. N_2, Ar and probably CO_2 could serve as pressurizing gases. The advantages of using CO_2 as a pressurizing gas is the fact that it is available from the Martian atmosphere and the simplified atmospheric control system. Furthermore, a high CO_2 level provides good fire suppression. Oxygen partial pressure will typically be maintained under 23.5% of the total pressure to avoid safety concerns related to oxygen enriched environments. These constraints are shown in figure 3-7. [Lacey, 1999]

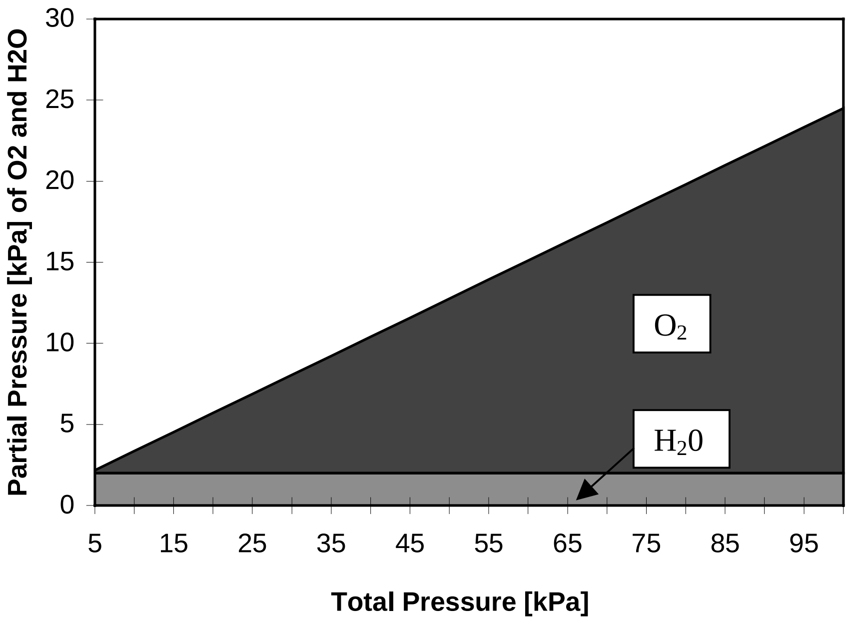


Figure 3-7: Constraints for O2 and H2O Partial Pressure for Low Pressure Greenhouses [Lacey, 1999]

Experiments indicated that no plant growth is possible at a partial oxygen pressure below 5 kPa. By constraining the oxygen partial pressure below 23.5%, the lower limit for the total pressure is determined at 21 kPa. Reduced plant growth is possible at a partial oxygen pressure of 7 kPa resulting in a total pressure of 30 kPa. The composition of a low pressure greenhouse atmosphere with a total pressure of respectively 21 kPa and 30 kPa is indicated in table 3-6. [Lacey, 1999]

Table 3-6: Examples for Composition of Low Pressure Greenhouse Atmospheres [Wheeler, 1999]

	21 kPa Atmosphere	**Comment**	**30 kPa Atmosphere**	**Comment**
Essential Gases	5 kPa O_2 2 kPa H_2O	saturation pressure of H_2O 2.3 kPa at 20°C	7 kPa O_2 2 kPa H_2O	saturation pressure of H_2O 2.3 kPa at 20°C
Pressurizing Gases	≤ 1 kPa CO_2 13 kPa N_2/Ar	or 14 kPa CO_2, if plant growth is feasible at high CO_2 levels	≤ 1 kPa CO_2 20 kPa N_2/Ar	or 10 kPa CO_2 11 kPa N_2/Ar
Total Pressure	21 kPa	~0.2 atm	30 kPa	~0.3 atm

Current studies at NASA's Kennedy Space Center demonstrate plant growth is possible in high CO_2 level environments. Plants were exposed to partial CO_2 pressures of 0.5-1.0 kPa. Most of the crops did not show any effect in terms of reduced biomass although certain crops showed toxic effects such as leaf injury. Generally, the water use of the crops increased due to increased transpiration. [Wheeler, 1999; Lacey, 1999]

The results of the tests indicate a wide range of plant responses to increased CO_2 levels. They have to be looked down on a crop-to-crop basis. Although the testing is still in the early stages, it showed plant growth in low pressure environments with increasing CO_2 level is feasible. Further investigations of plant responses to very high CO_2 level environments (1.0-15.0 kPa) are needed. It has to be studied if high humidity can be maintained as the transpiration increases with increased CO_2 level. Future studies should include different greenhouse atmosphere compositions, e.g. utilization of Nitrogen and Argon as pressurizing gases, extracted from the Martian atmosphere. [Wheeler, 1999; Lacey, 1999]

3.1.5.3.2 Temperature, Humidity and Ventilation

Temperature, humidity and ventilation can be optimized to produce maximum yields. Table 3-7 lists typical growing conditions for plants.

Table 3-7: Plant Growth Requirements [Eckart, 1996]

PROPERTY	VALUE
Temperature [°C]	15-28
Humidity [%]	50-85
Air Flow [m/s]	0.1-1.0

The thermal control system must maintain the greenhouse temperature within a relatively narrow range (15-28° C) for efficient plant growth. Experiments show that high temperature (25° C) increases growth rates but reduces the yields. On the other hand, cool temperatures (20° C) tend to increase yields but slow down growth rates. Together with the other factors, temperatures should be optimized for each phase of the life cycle. Humidity levels have a strong influence on plant transpiration. The relative humidity has to be optimized to maintain efficient transpiration rates. High humidity can result in a low cooling capacity and therefore in high leaf temperatures. Moreover, if humidity is too high this could lead to corrosion and growth of various microorganisms. Air movement is important for convective heat transfer and transpiration. Temperature, humidity and ventilation will have to be controlled by physical components, such as heat exchangers and fans. [Eckart, 1996]

3.1.5.4 Lighting Requirements

For the photosynthesis process light has to be provided to the plants (see section 3.1.5.1). The productivity of the plants depends on the light intensity, the light duration and the spectral composition. The amount of edible biomass that would be grown increases with increasing photo-synthetically active radiation (PAR) (see section 3.1.5.1). Sunlight provides a PAR level of 2000 $\mu mol/(m^2\ s)$ on a clear day on Earth. The lower limit for the PAR level, where plant growth is still possible, is 200 $\mu mol/(m^2\ s)$. Every crop species can cope with an individual maximum lighting period. Soybean and peanuts, for example, should not be exposed to light for more than 12 hours, whereas the lighting period of wheat can last for up to 24 hours. The maximum lighting period for ALS crops is given in table 3-8. In general, longer lighting periods permit lower irradiance. [Eckart, 1996]

Table 3-8: Lighting Period of ALS Crops [Heyne, 1999]

MAXIMUM LIGHTING PERIOD	**CROPS**
12 h	soybean, white potato, sweet potato, rice, peanut
16 h	carrot, cabbage, lettuce, celery, green onion, strawberry, spinach, pea
18 h	tomato, dry bean, peppers, snap bean
24 h	wheat

For plant growth a special part of the spectrum is of interest, i.e. the visible spectrum with wavelengths between 400 and 700 nm. As it can be seen in figure 3-8, plants absorb especially the red wavelengths of about 430 nm and the blue wavelengths of about 670 nm, while the green wavelengths of about 550 nm are reflected. That is the reason why plants appear to be green. [Eckart, 1996]

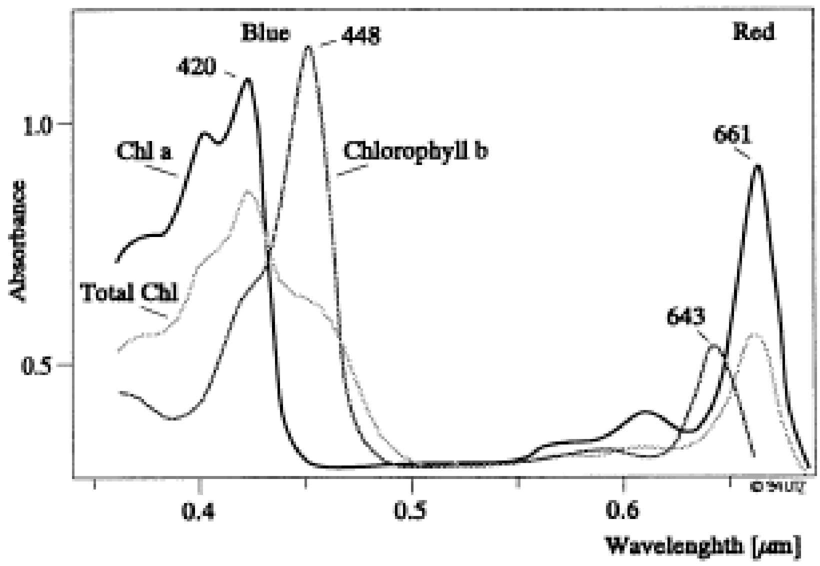


Figure 3-8: Light Absorption Spectra of Plants [Eckart, 1996]

3.2 Inflatable Structures

In the late 1960's several inflatable structures were designed for space applications. They were tested successfully, but never used as metallic structures were chosen for the moon program. During the 60's, 70's and 80's NASA relied on those rigid, mostly aluminum structures since they were known to be safe and proved to be reliable. The idea of designing inflatable structures was reborn when the textile industry introduced new fiber materials like Kevlar and Vectran. Inflatable structures promise lighter mass at a lower cost. Furthermore, the architecture is not longer restricted to cylindrical modules. [Kennedy, 1999]

3.2.1 Requirements and Constraints

In this document flexible composite inflatable structures are selected as a basis for the greenhouse design as they offer many advantages over conventional structures. The most important benefit is the ability to fold the inflatable structure into small volumes of various shapes for launch. This capability leads to huge mass savings and therefore reduced launch costs by increasing the usable volume once deployed. The benefits of inflatable structures have been realized in several applications such as the Extravehicular Activity Space Suit, the Mars Pathfinder impact attenuation landing system and the TransHAB (see section 3.2.3). [Sandy et al., 1999]

An inflatable structure for a Mars greenhouse must meet several design and construction requirements: [Sadeh et al., 1993]

- Structural adequacy to sustain:
  - long-term loads produced by the internal pressure and the material weight
  - transient internal loads due to operation with an acceptable degree of safety
- Structural shape to resist imposed loads with a minimum of structural material
- Small stowage volume and light mass to minimize transportation cost and space
- Low volume to usable floor area
- Structural material of high strength, high ductility, high durability, high stiffness, high tear resistance, high puncture resistance, low thermal expansion, stable mechanical properties and low leakage (low permeability) (see section 3.2.2)
- Durability and reliability to resist deterioration with time due to material degradation from temperature cycles, radiation, chemical action, and other operational parameters
- Compatibility with the environment, heat management and rejection, and other support systems and structures
- Functional to efficiently and economically house and support the operations for which the structure is designed
- Modularity to facilitate easy and functional expansion
- Easy connectivity among the structural components
- Minimal construction equipment
- Minimum inspection, maintenance and repairs

Inflatable structures are in fact tensile fabric membrane pneumatic structures. As such they are inflated by air or by a fill material to stress the membrane in tension. There are three basic pneumatic structure types (see figure 3-9): [Kennedy, 1999]

- **Air-inflated**
  A multi-layer composite membrane is inflated by internal pressure. An air-inflated structure is ideal for vacuum and low pressure environments because it is stiffened by a difference in pressure between the inside and the outside surface of the volume. This characteristic eliminates the need for stiffened structural supports. An example for this structure type is NASA's TransHAB (see section 3.2.3).
- **Air-supported**
  A multi-layer dual membrane cavity relies on air pressure in the cavity wall to maintain the volume. This resulting volume can be pressurized at a lower pressure or no pressure at all.
- **Rigidized**
  A multi-layer membrane relies on change-of-state in materials to rigidize the shell upon deployment with a resulting volume that can be pressurized at a low pressure or not at all.

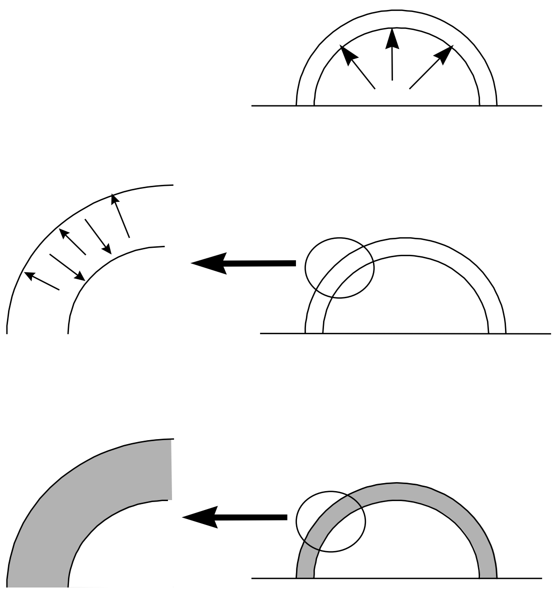


Figure 3-9: Basic Pneumatic Structure Types [Kennedy, 1999]

An air-inflated structure is essentially a pressure vessel since the internal pressure is by far the dominant loading as previously shown. The internal pressure induces only tensile stresses under proper design. The design and shape of the tensile membrane structure is controlled by the internal pressure. In a tensile membrane structure, loads are predominately resisted by direct tensile forces and the shape of the structure. Any change in direction of the tensile force following the curved structural surface over some finite size of the membrane equilibrates the applied transverse load at that region. Smaller loads, such as point loads, can distort the overall shape slightly and lead to local movements of the membrane. A curved membrane is much more efficient structurally than a system involving flexure. [Sadeh et al., 1993]

The most efficient tensile membrane structure is a sphere since it contains the most volume relative to the surface area. A cylindrical structure is less efficient than a sphere but widely used as the functional advantages offset its reduced structural efficiency. The design of an inflatable membrane structure for a greenhouse involves the compromise among a tensile shape which is structurally efficient, a shape which provides the required growth area, and the associated construction restraints. The optimum structurally efficient shape has to meet the functional and construction requirements. [Sadeh et al., 1993]

3.2.2 Materials

The structure of the inflatable greenhouse has to enclose the air, support the internal pressure and protect the interior from the hostile Martian environment. There are numerous materials available for use in greenhouse structures. For the selection of the material the requirements of the system summarized in table 3-9 have to be considered. Table 3-10 shows the candidate materials and their properties. [Sandy et al., 1999]

Table 3-9: Requirements on the Material [Sandy et al., 1999]

REQUIREMENT	FUNCTION/COMMENT
high strength with safety factor	for supporting membrane loads and local rock induced loads
low mass	reduction of launch costs
high flexibility	for packaging
low outgassing ability	into and from the greenhouse
thermal protection	optical properties
cycle life	pressurization/deployment/thermal
environmental resistance	radiation/thermal
puncture/tear resistance	to survive rocky impacts
retention of strength after flex/crease	layers tightly packed for months prior to deployment
low coefficient of friction	to mitigate dust settlement on greenhouse surface

Table 3-10: Properties of Candidate Materials [Sandy et al., 1999]

FIBER	DACRON TYPE 68	SPECTRA 1000	VECTRAN HS	KEVLAR 29	TECHNORA	ZYLON HM
MATERIAL TYPE	Polyester	Poly-ethylene	LCP	Aramid	HT Aramid	PBO
TENACITY @ BREAK (g/d)	8.4	33	23	22	28	42
MODULUS (N/mm^2)	0.14×10^5	2.0×10^5	0.6×10^5	0.7×10^5	0.7×10^5	0.27×10^5
ELONGATION @BREAK (%)	17	3.4	3.30	3.6	4.6	2.5
DENSITY (g/cm^3)	1.38	0.97	1.4	1.44	1.39	1.56
TEMPERATURE LIMITATIONS	Melts at 256° C.	Melts at 149° C. Exhibits creep with increasing temp.	Melts at 329° C. Tensile strength ↑ as temp. ↓	Decomposes at 427° C. Tensile strength remains fairly constant with temp.	Decomposes at 550° C. Tensile strength remains fairly constant with temp.	Decomposes at 427° C. Tensile strength remains fairly constant with temp.

An advantage of using Vectran regarding the low temperatures on Mars would be the increase of tensile strength as the temperature decreases. Vectran is a liquid crystal polymer film manufactured by Hoechst-Celanese. With comparable yarn tenacity to Kevlar 29, it has better flex-crack/abrasion resistance. Kevlar fibers are more readily damaged by flexing and sliding against themselves, when the fabric is folded. While Kevlar offers more strength retention at higher temperatures than Vectran, Vectran retains its full strength upon cooling and gets actually stronger at low temperatures. Silicone coated Vectran was selected as the bladder material for the Mars Pathfinder airbags, its properties are given in table 3-11. [Sandy et al., 1999]

Table 3-11: Properties of Silicone coated Vectran used for Pathfinder Airbags [Sandy et al., 1999]

PROPERTY	VALUE
Basic Vectran Fabric	
Yarn	200 denier Vectran HS
Weave	50 x 50 plain weave
Weight	0.09 kg/m^2
Tensile strength	7134 kg/m
Tear strength	68 kg
Coated fabric	
Coating	**Silicone rubber**
Coating adhesion	3.8 kg
Coating weight	0.054 kg/m^2
Coated fabric weight	0.15 kg/m^2

In order to achieve structural restraint, Kevlar webbings were chosen for the TransHAB (see section 3.2.3) to hold the module's shape. The properties of Kevlar are summarized in table 3-12.

Table 3-12: Properties of Kevlar used for TransHAB [Ortiz, 2000]

PROPERTY	VALUE
Yarn	
Yarn Type	1,500 denier Kevlar 29
Density	1.44 g/cm^3
Tensile properties	
Breaking strength	338 N
Breaking tenacity	22 g/d 2,920 MPa
Tensile modulus	555 g/d 70,500 MPa
Elongation at break	3.6%
Thermal properties	
Specific heat at 25 °C at 100 °C at 180 °C	 1,420 J/(kg x K) 2,010 J/(kg x K) 2,515 J/(kg x K)
Thermal conductivity	0.04 W/(m x K)
Decomposition temperature in air	427 - 482 °C
Recommended max. temperature in air	149 - 177 °C

3.2.3 TransHAB

NASA JSC is currently working on a program to develop an inflatable habitat structure to be used as a transfer vehicle to Mars and proposed to the International Space Station (ISS) as a replacement for the current HAB module. The inflatable composite structure is packaged around a metallic center core in order to decrease the initial volume for launch. On orbit it will be inflated to a total volume of 350 m^3 (approximately 8 m diameter, 11 m length). The high packaging efficiency allows one single Shuttle launch compared to two Shuttle launches that would be required for the equivalent volume of a rigid structure. [Sandy et al., 1999; NASA Fact Sheet: TransHAB, 1999]

The inflatable structure is a series of material layers performing functions as the gas retention, structural restraint, material and orbital debris protection, thermal protection and radiation protection (see figure 3-10). Gas retention is achieved by a redundant bladder assembly. The air is held inside by three layers of Combitherm, a material commonly used in the food packaging industry. Each individual bladder layer is a laminate of polyethylene, nylon, ethylene vinyl alcohol, and polyethylene film. The resultant laminate is an ultra low permeable film. The most inner layer, forming the inside wall of the module, is Nomex cloth, a fireproof material that also protects the bladder from scuffs and scratches. Structural restraint is achieved by a series of Kevlar (see section 3.2.2) webbings that are interwoven and indexed to one another to hold the module's shape. The webbings are sized to withstand the 101 kPa internal pressure load of the ISS with a safety factor of 4. Consequently, the structure must withstand approximately 1.57×10^5 kg/m maximum stress in the hoop direction and 0.63×10^5 kg/m stress in the longitudinal direction. Other materials like Vectran (see section 3.2.2) are also being considered in flight configuration. [Sandy et al., 1999; NASA Fact Sheet: TransHAB, 1999]

The micrometeoroid and orbital debris protection is being accomplished by a series of woven 1.5 mm thick Nextel layers separated by foam spacers to create a multi-hull structure. This structure was tested for particle impact at JSC and proved to provide a greater protection than the rigid ISS modules. These tests showed that particles of up to 1.8 cm traveling at a speed of 7 km/s would not penetrate the structure. The Nextel layers were coated with polyethylene to enhance their stability. The polyethylene also provides a significant amount of radiation protection. Thermal protection is accomplished by a series of metallized films on the exterior of the assembly that reflect radiation. The values for the effective emittance and for the effective conductivity for the complete TransHAB shell were measured at $\varepsilon_{eff} = 0.05$, and $k_{eff} = 0.14$ W/(m x K). [Sandy et al., 1999; Ortiz, 2000]

A hydrostatic test in the JSC Neutral Buoyancy Lab facility demonstrated successfully that the restraint layer would handle loads of 4.0 times the maximum operating pressure it would see on the ISS. The test was performed by virtually inspecting the full diameter test shell underwater verifying there were no anomalies in any of the restraint layer webbing and stitches. A full-scale inflatable shell was folded and packaged for launch to be used for the next test. It was deployed and inflated under vacuum conditions in a thermal vacuum test chamber. These tests represent a significant milestone for NASA in the development of inflatable structures. An overview of the TransHAB concept is given in figure 3-11. [Sandy et al., 1999]

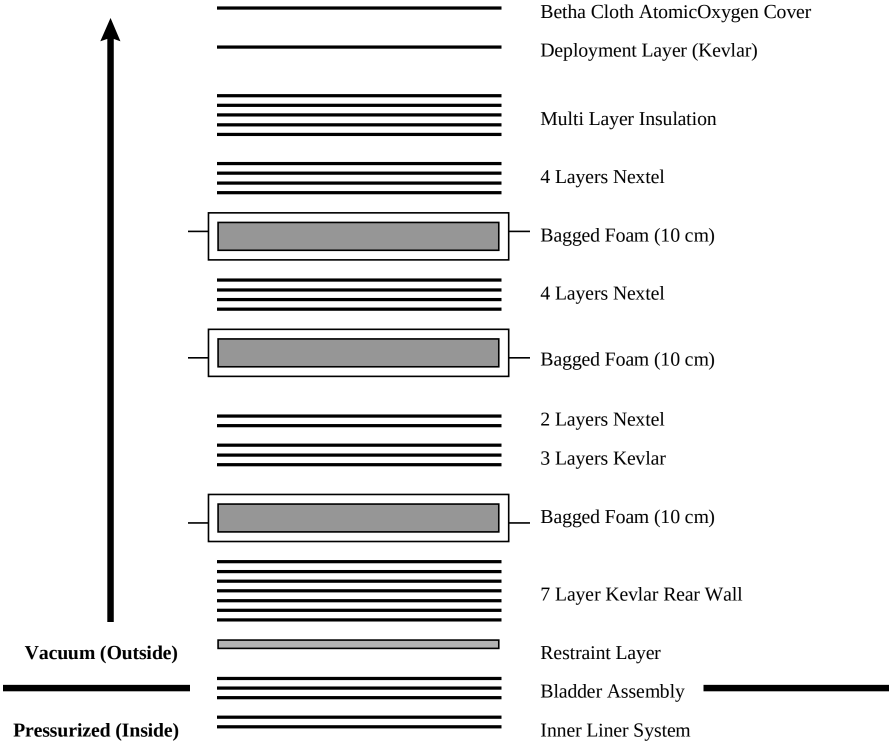


Figure 3-10: TransHAB Shell Buildup [Ortiz, 2000]

Figure 3-11: TransHAB Concept Overview [NASA Fact Sheet: TransHAB, 1999]

3.2.4 Inflatable Greenhouse Structure

Composite inflatable structures require three principal components or materials: [Kennedy, 1999]

- The first component is intended for structural load bearing purposes, and usually consists of high tenacity fibers to react stresses associated with the structure.
- The second component is an impermeable gas barrier needed to minimize air loss inside the module.
- The final component is a joining or matrix material whose function is to maintain alignment of the other components, particularly while folded and during deployment, and while pressurized, to transfer loads between structural elements by inter-laminar shear.

For the inflatable greenhouse an air-inflated structure similar to the TransHAB shell concept is chosen. Gas retention is achieved by a redundant bladder assembly, whereas structural restraint is achieved by Kevlar webbings. For radiation protection a dome could be deployed. This shell concept is depicted in figure 3-12. The shell assembly depends mainly on the lighting method. If it is foreseen to use natural sunlight the shell assembly has to be highly translucent. If artificial lighting is used an opaque multi-layer insulation can be installed to prevent the heat loss during the night. The bladder is triple redundant with vacuum between the individual layers. If, for example, the innermost layer leaks there are still two layers left to ensure the gas retention. Vacuum sensors can be installed between the layers to detect possible leakage. The greenhouse shell assembly in relation to the lighting method is shown in figure 3-13. [Kennedy, 1999]

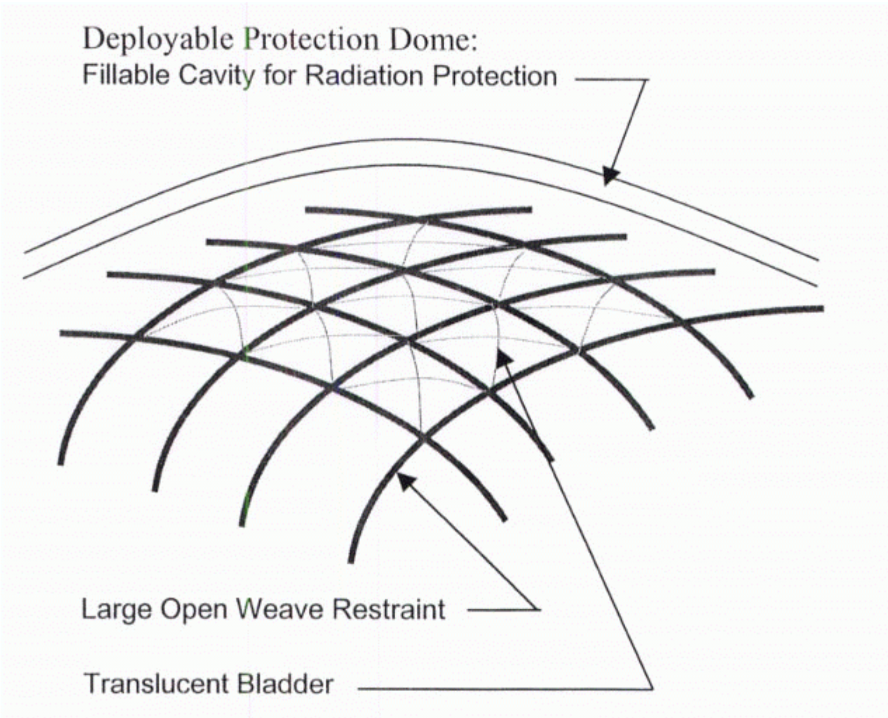


Figure 3-12: Inflatable Greenhouse Shell Concept [Kennedy, 1999]

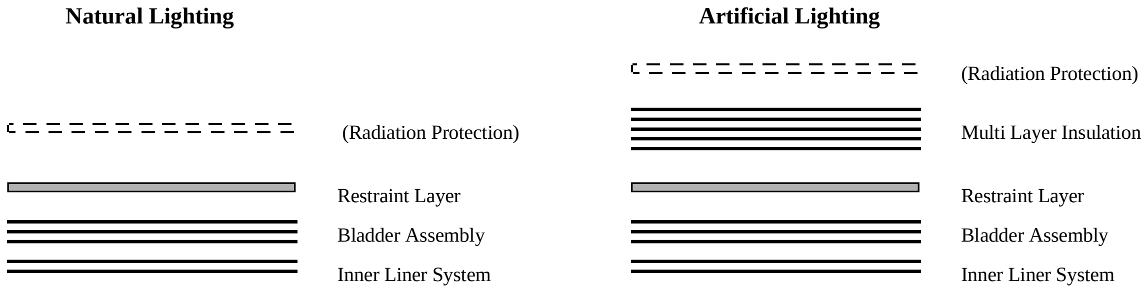


Figure 3-13: Greenhouse Shell Assembly in Relation to the Lighting Method [Kennedy, 2000]

The same bladder will be used for the high pressure (60 kPa) and the low pressure (30 kPa) greenhouse. For the low pressure greenhouse the pressure difference between the inner greenhouse atmosphere and the outer Martian atmosphere is lower than the pressure difference for the high pressure greenhouse. Consequently, the restraint layer for the low pressure greenhouse does not have to provide the same structural restraint and can be lighter. In order to achieve this, either the gaps between the open weave are designed wider or the restraint will be thinner. In table 3-13 the mass of the bladder and the restraint layer is given for both the high pressure (60 kPa) and the low pressure (30kPa) greenhouse. [Kennedy, 1999]

Table 3-13: Mass per Area of the Greenhouse Surface Materials [Kennedy, 1999]

MATERIAL	**HIGH PRESSURE GREENHOUSE 59.2 kPa**	**LOW PRESSURE GREENHOUSE 30.0 kPa**
Bladder (polyethylene)	1.22 kg/m^2	1.22 kg/m^2
Restraint Layer (Kevlar)	1.31 kg/m^2	0.66 kg/m^2
Multi-Layer Insulation (Mylar, Beta Cloth)	1.22 kg/m^2	1.22 kg/m^2

3.3 Lighting

An important environmental factor for plant production is the lighting, as it is required for the photosynthesis process which transforms carbon dioxide into oxygen while producing new biomass (see section 3.1.5.1). For a plant production system basically four options of lighting methods can be considered: [Eckart, 1996]

- Natural solar lighting via transparent materials.
- Solar light collection and distribution system such as fiber optics.
- Artificial lighting with lamps.
- Hybrid lighting (combination of natural and artificial lighting).

Table 3-14 summarizes the advantages and disadvantages of the lighting methods which will be discussed in this section.

Table 3-14: Advantages and Disadvantages of Lighting Methods

LIGHTING METHOD	ADVANTAGES	DISADVANTAGES
Natural Lighting	- no additional power needed - no additional mass needed	- low PAR level on Mars - only available during Martian day - low radiation and micro-meteoroid protection - diurnal heat gain/loss - large growth area for low PAR level on Mars
Solar Light Collection and Distribution	- no power needed - high radiation and micro-meteoroid protection possible	- low efficiency - high mass of system - relative new technology
Artificial Lighting	- high PAR level - 24 hours lighting possible - lighting intensity, duration and spectrum can be adjusted to plant needs - high radiation protection possible - reduced growth area for high PAR level	- high mass and power requirements for lamps - heat rejection required
Hybrid Lighting	- use of natural PAR	- mass and power depend on additional lamps

3.3.1 Natural Solar Lighting

The use of direct natural sunlight via transparent materials can save considerable mass, power and heat rejection resources that would be otherwise required for artificial lighting. In Earth orbit the solar constant is 1353 W/m^2. The solar light constant for Mars Orbit, 590 W/m^2, is only 43% of Earth's (see table 2-4). A global dust storm may degrade the solar irradiance on the surface of Mars to 100 W/m^2, which is about the same of a cloudy day on Earth. The lower limit for the solar irradiance where plant growth is still possible is 200 W/m^2. So, even during a global dust storm about half of the required plant lighting can be achieved by direct solar illumination. The relation between the amount of edible plant mass and the amount of natural light in section 3.1.5.1 shows that the plant growth rate decreases with decreasing photo-synthetically active radiation (PAR), i.e., with decreasing solar irradiance. Consequently, the productivity of a greenhouse with exclusively natural lighting depends mainly on the Martian season. Mass and power for the lighting systems and heat rejection resources can be saved in comparison to artificial lighting, but the gain in mass savings would probably be lost as the growth area increases with decreasing PAR level. As seen in section 3.1.5.1 a greenhouse using natural sunlight requires a larger growth area than a greenhouse with artificial lighting providing a high PAR level. [Clawson, 1999]

3.3.2 Solar Light Collection and Distribution

Light collectors could reduce concerns of transparent materials such as fractures from micro-meteoroid impacts or high radiation level inside the greenhouse. This system is designed to collect the useful visible wavelengths, whereas harmful frequencies such as infrared and ultraviolet light are not collected. Solar light can be collected in larger areas than the actual greenhouse surface. Light collection systems have been investigated in the past, but showed a low transmission efficiency of 50%. Additional to the solar light, artificial light could be distributed into the system. This concept results in lower heat gains as the waste heat of the lamps is released outside the greenhouse. Regarding the low efficiency of the light collection and the high system mass, the light collection and distribution system is not expected to be feasible for Mars applications. [Eckart, 1996; Clawson, 1999]

3.3.3 Artificial Lighting

The amount of edible biomass that would be grown increases with increasing PAR (see section 3.1.5.1). High PAR levels can be achieved by using electrical light. In principle maximum PAR level is desirable, irradiance level will be limited by heat and power constraints. Artificial lamps have to provide the wavelengths most useable by the plants, i.e., the visible wavelengths (see section 3.1.5.4). [Eckart, 1996]

Table 3-15 summarizes the power allocations of different types of electrical lamps. Although the highest efficiency (27%) for conversion of electrical power to PAR in the 400-700 nm range is provided by low pressure sodium lamps (LPS), these lamps provide an essentially monochromatic light which may not be suitable for all varieties of higher plants. A number of lamp types have conversion efficiencies in the 20-30% range and provide emission spectra, which are more acceptable to a diversity of higher plants. The second most efficient lights (25%) are high pressure sodium lamps (HPS). The 400 W HPS lights were selected for the BIO-Plex project. Their characteristics are given in table 3-16. HPS generate intense, localized heat loads and therefore require a high mass of cooling equipment. If, for example, a PAR level of 1000 μmol/(m^{2}s) would be required, the mass for the required 5.1 lamps per area would be 1.071 kg/m^2, compared to a mass of 7.02 kg/m^2 that would be needed as cooling equipment. [Schwartzkopf, 1990]

Table 3-15: Power Allocation of Light Sources [Schwartzkopf, 1990]

LAMP TYPE	TOTAL INPUT POWER [W]	VISIBLE RADIATION [%]	NONVISIBLE RADIATION [%]	CONDUCTION AND CONVECTION [%]	BALLAST LOSS [%]
Incandescent:					
60 A	60	6	84	10	0
100 A	100	7	83	10	0
200 A	200	8	83	9	0
Fluorescent:					
Cool White (FCW)	46	20	32	35	13
Cool White (FCW)	225	20	37	39	4
Warm White (FWW)	46	20	32	35	13
Plant Growth A (PGA)	46	13	35	39	13
Plant Growth B (PGB)	46	15	35	37	13
Clear Mercury (HG)	440	12	63	16	9
Mercury Deluxe (HG/DX)	440	13	64	16	9
Metal Halide A (MHA)	460	20	54	13	13
Metal Halide B (MHB)	460	22	52	13	13
High Pressure Sodium (HPS)	470	25	47	13	15
Low Pressure Sodium (LPS)	230	27	25	26	22

Table 3-16: Data of High Pressure Sodium Lights [Drysdale et al., 1999]

PARAMETER	VALUE
Lamp power (not including ballast) [kW]	0.4
Lamp mass [kg]	0.21
Lamp life [h]	20000
Number of lamps per area to give 1000 μmol/(m^2s) [lamp/m^2]	5.1
Crew-time to change out lamps [ch]	0.03
Hours of lighting usage per day [h]	10-24
Lamp volume for resupply [m^3]	0.000625
Ballast power [kW/lamp]	0.06
Ballast mass [kg/lamp]	4.76 - 9.52
Mass of coldplate, water barrier, condensing heat exchangers per growth area [kg/m^2]	7.02
Height of lighting assembly [m]	0.15
Lamp resupply mass factor	1.5
Lamp resupply volume factor	1.5

3.3.4 Hybrid Lighting

Despite the advantages of direct solar illumination, a stay on the Martian surface may require supplemental artificial light sources because of the degradation in solar irradiance resulting from storms on the Martian surface (see table 2-4). Nevertheless, even with severe degradation of solar irradiance, such as by Martian global dust storms, any amount of direct solar illumination can help to decrease the mass, power and heat rejection requirements of artificial lighting.

3.4 Thermal Control System

Temperature control of the inflatable Mars surface greenhouse will be extremely challenging. On the surface of Mars, in contrast to free space, excess heat can not easily be dumped with radiators. [Schwarzkopf, 1990]

The thermal properties of the greenhouse shell depend on the shell assembly (see figure 3-13). The goal of a greenhouse with natural lighting is to let in as much light as possible to ensure the productivity of the plants. Therefore, the transmittance has to be very high. The value for the transmittance of the TransHAB bladder material is 75%. It is assumed that the restraint webbings reduce the transmissivity of the shell by approximately 20% for high pressure, 10% for low pressure. Thus, the transmittance of the shell for a greenhouse with natural lighting can be estimated at 55%, resp. 65%. The emissivity of the greenhouse shell is 1.0 for the heating requirement calculation and 0.8 for the cooling requirement calculation. [Schwarzkopf, 1990; Ortiz, 2000; Ewert, 2000]

A multi-layer insulation is added to the shell of the greenhouse using artificial lighting (see figure 3-13). This opaque layer reduces the transmissivity to 0%. The emissivity is reduced to 0.05. The thermal properties of a greenhouse shell in relation to the lighting method are listed in table 3-17. [Ortiz, 2000]

Table 3-17: Thermal Properties of a Greenhouse Shell in Relation to the Lighting Method [Ortiz, 2000]

PROPERTY	NATURAL LIGHTING	ARTIFICIAL LIGHTING
Transmittance	0.55 (high pressure) 0.65 (low pressure)	→ 0
Emissivity	>0.80	0.05

3.4.1 Greenhouse with Natural Lighting

A natural greenhouse is designed as light transparent shelter to provide environmental conditions for plant production protecting plants from a hostile environment. It is extremely important to control the greenhouse climate in order to have a maximal effect of the production factor light. The crop production and its interaction with the environmental conditions are extremely complex. More and more information about the relation between crop growth and environmental conditions is gathered by studies in order to optimize the growth by controlling the desired temperature and humidity level. [Hashimoto et al., 1993]

The set of environmental factors inside the greenhouse affecting crop growth and development is referred to as the greenhouse climate. The differences between the climate inside a greenhouse and the environmental conditions on Earth are the following: [Hashimoto et al., 1993]

- **Enveloping of air:** The air in the greenhouse is stagnant due to the enclosure. Consequently, the lower air velocities affect the exchange of heat, water vapor and carbon dioxide and the greenhouse inventory (crop, surface, heating system).
- **Radiation:** The incoming short wave radiation (direct from the sun and scattered from the sky, clouds and by small particles in the Martian atmosphere) is decreased due to the light interception by the opaque and transparent components of the greenhouse while the long wave radiative exchange between inside and outside the greenhouse is changed due to the radiative properties of the covering material. The radiation affects directly the air temperature inside the greenhouse.

The greenhouse climate is a complex interaction of various physical processes. Quantification of this climate as affected by the dynamic outdoor weather conditions and the physical properties of the greenhouse itself demand quantification of the various exchange processes. Only for control purposes can the model be simplified and restricted to relations of interest. Then the extensive model as a representation of the main characteristics of the real system can be used to validate the simplified one. [Hashimoto et al., 1993]

The production in a greenhouse is aimed at an optimal exploitation of incoming direct and diffuse solar radiation as driving force for the photosynthesis process (see section 3.1.5.1). For plant growth a special part of the spectrum in the visible region is of interest, the photo-synthetically active radiation (PAR) with wavelength region in the visible spectrum between 400 and 700 nm. In this region about half of the solar energy is irradiated. Only a small part of the PAR energy is directly converted into the photosynthesis process. The total solar radiation at crop level contributes to the energy balance of the crop, so that it affects crop temperature and transpiration. The interaction of the solar radiation with the greenhouse cover determines how much radiation is transmitted and available at crop level. This interaction can be calculated from the basic optical laws for reflection, absorption and transmission of transparent layers and opaque construction parts. Therefore the optical properties of the transparent materials, the angle between radiation relative to the observed surface and the geometry of the construction have to be known: [Hashimoto et al., 1993]

- For the **direct light**, the angle between radiation and surface results from the solar position (given by the latitude of the greenhouse and the time and date) and of the orientation and geometry of the surface.
- For the **diffuse radiation**, the angle results from the distribution of the radiation intensity over the hemisphere. This distribution varies according to the meteorological conditions. The most striking difference is between a clear sky and a global dust storm on Mars.

The **thermal radiation** exchange from the greenhouse interior to outside is shielded by the cover. The efficiency of this shield depends on the radiative properties in the thermal wave length region (5000 - 50000 nm for environmental temperatures). Inside the greenhouse the various surfaces exchange radiation. The energy exchange by radiation from the greenhouse surface to the Martian environment can be calculated according to the Stefan-Boltzmann relation, implementing emission coefficients to account for the radiative properties of the surface: [Schwarzkopf, 1990; Ewert, 2000]

$$q_{1,2} = \varepsilon_{1,2}\, b\, (T_1^4 - T_2^4)$$

where:

$q_{1,2}$ = energy flux density due to thermal radiation from surface to environment (W/m^2)
$\varepsilon_{1,2}$ = combined emissivity between the surfaces and the environment (-)
b = Stefan-Boltzmann constant (5.67×10^{-8} $W/[m^2 \times K^4]$)
T_1 = temperature of surface (K)
T_2 = temperature of environment (K)

The view factors for the thermal radiation exchange between the crop and the other greenhouse parts are dependent on the development of the crop. They have to be determined in a separate study on the physical behavior of the crop. [Hashimoto et al., 1993]

3.4.2 Greenhouse with Artificial Lighting

A greenhouse using artificial lighting is designed as an opaque shell. The thermal properties of the greenhouse depend mainly on the outer multi-layer insulation (MLI). As no light penetrates through the MLI the transmissivity is equal to zero. The heat loss through emission is very low due to the low emissivity of an opaque greenhouse. The main impact on the thermal system has the heat gain resulting from the waste heat of the lighting.

3.5 Operation and Maintenance

3.5.1 Atmosphere Management

The major obstacle of operating a greenhouse is not a major failure but the maintenance of the greenhouse. The success of operating a greenhouse lies in its details. It is relatively easy to support the temperatures and gas composition but very hard to control the trace contaminants. Experiments aboard the MIR space station demonstrated the difficulties of running a biological experiment for weeks. For example, a wheat experiment failed because of the trace contaminant ethylene in the air. The wheat grew normally but it did not produce any seeds. Biosphere 2 in Arizona and the Russian BIOS 3 experiment showed that ecological balance is impossible with low buffer capacities. Stability in an artificial environment can only be achieved by technological control. [Schuerger, 1999]

Special attention should be paid to the hygiene requirements. Microorganisms are always carried with us by accident. Their survival depends on environment pressure, radiation and temperature. A low pressure environment leads to an increase of the microorganisms. Experiments demonstrated that beneficial species decreased upon closure, whereas pathogenic species increased upon closure. Layers of microorganisms and fungi, so-called biofilms, can develop and alter the functions of the biological life support system. To prevent such biofilms and the appearance of diseases of the crew as the human immune system is depressed upon closure, the greenhouse has to be cleaned and disinfected periodically in order to remove bacteria, microorganism and fungi. [Schuerger, 1999]

The presence of pest management will likely exclude many plant pathogens that are typically encountered in terrestrial agricultural systems; but total exclusion of all pathogens is unlikely. Thus, effective methods for managing microbial populations inside the greenhouse will have to be developed to ensure long term viability of space-based plant growing systems. Studies on the impact of spectral composition on plant diseases should be included in the pest management program. [Schuerger, 1998]

3.5.2 Servicing and Harvesting

The plants have to be seeded, serviced and harvested. To minimize the need for crew interaction, automation for the plant growth module should be implemented. This could be realized by using three automation devices for each greenhouse: [Hanford, 1997]

- The **first device** would seed and plant modular trays.
- A second automation device, a **gardening robot**, would transfer the trays to growing racks where the plants would develop and mature under natural, hybrid or artificial lighting. The gardening robot would also tend the crop during the growth period. At harvest time the gardening robot would transfer the tray to the third device.
- The third device, the **harvester**, would remove the crops from the growing tray.

An automation scheme for surface-based plant growth systems is still not well defined. Table 3-18 presents the preliminary overall values for the three automation devices.

Table 3-18: Values for Automation Devices [Hanford, 1997]

PARAMETER	VALUE
Mass	337.3 kg
Power	0.046 kW
Volume	2.8 m^3

3.5.3 Dust Removal from Greenhouse Surface

Onboard the Mars Surveyor Lander to be launched in April 2001 there will be the Mars In-Situ-Propellant-Production Precursor (MIP) payload. MIP consists of five distinct experiments, one of them will be the Dust Accumulation and Repulsion Test (DART). The objectives of the DART experiment will be the measurement of the power loss of solar cells due to settling of airborne dust, the measurement of the characteristics of deposited dust and test methods of preventing dust accumulation by electrostatic dust repulsion and tilted surfaces. The utility of a dust removal technique for the Mars surface greenhouse depends on the detailed properties of the surface dust, including composition, binding strength, particle size distribution, native charge, and surface chemical state. [Kaplan et al., 1999]

Observations by the Viking landers seemed to show that dust did not build up on tilted surfaces. Unfortunately, no quantitative measurements of accumulation could be made. DART seeks to verify the conjuncture that tilted surfaces do not accumulate dust and to get an indication of the angle required to avoid dust coverage. This angle will have a strong influence on the future design of Mars surface greenhouses. As Martian atmosphere is expected to be charged another technique to mitigate the dust settling on the greenhouse surface could be electrostatic fields. If the dust cannot be removed naturally by tilted surfaces or electromechanically by electrostatic fields dust removal could be accomplished by astronauts and machines wiping or blowing the dust off the surface. [Kaplan et al., 1999]

3.6 Equipment

Though plant production for space missions has been extensively studied, space-compatible technologies for processing crops and preparing ready-to-eat meals have yet to be developed. These processing and preparation problems constitute a major engineering challenge for food systems in space. For the processing and preparation of the plant material into acceptable food, certain equipment is analyzed, including the following: [Parks et al., 1994]

- Extruder
- Grain/flour mill
- Soy milk machine
- Food processor
- Bread machine
- Dishwasher
- Refrigerator
- Freezer
- Dehydrator
- Press (oil extraction hydraulic)
- Pasta press
- Automatic tofu/milk machine
- Galley
- Stovetop
- Toaster oven
- Mixer
- Convection oven
- Bagel maker
- Blender

The necessary equipment has to be chosen according to the diet and selected plants, by considering the minimization of mass and power requirements. The mass of food processing equipment for a crew of four is estimated to be about 655 kg. However, this is a very preliminary estimate. [Parks et al., 1994; Duffield, B.E. 2000; Drysdale et al., 1999]

Furthermore, equipment for the harvesting and planting of the crop is required: [Duffield, B.E. 2000]

- Tray lid conveyer
- Tray lift
- Processing conveyer
- Tray lid (support frame, rooting matrix)
- Automated seeder
- Harvester
- Germination cabinet
- Crop dryer

3.7 Interfaces

An important feature of any pressure vessel is the use of interfaces to connect it to other pressurized modules as well as utilities. The inflatable greenhouse requires both internal and external interfaces. These interfaces are critical to the overall system's capability and performance. Water, gas, fluids, power and data are passed through the interfaces and connected internally to the plant growth system. The more interfaces are required the higher is the risk of potential failure areas or leaks (fluid/gas). Interface connections play an important role of an inflatable greenhouse and have to be considered carefully during the design process. [Kennedy, 1999]

The external structure interface has to connect the greenhouse to the interconnecting tunnel (see figure 4-2). Interfaces have to ensure the power and data supply. Furthermore, thermal and water supply has to be established by interfaces. The wastewater has to be led into the greenhouse for recycling and the gas-exchange should be considered. Therefore, internal pumps, cabling, lines and tubes have to be allocated while special attention has to be paid to line length limits and bend radii. Another critical factor is the air-exchange for a low pressure greenhouse. Air cannot be exchanged directly with the habitat as the pressure and the air composition differ from the one in the habitat (see section 3.1.5.3.1). [Kennedy, 1999]

3.8 Packaging and Assembly

The inflatable greenhouse is classified as a prefabricated constructable habitat, because it is fabricated on Earth, transported via smaller manageable elements, and then assembled on the Martian surface. The major elements to assemble are the mat foundation, inflatable structure, internal flooring system, air supply and inflation system, regenerative life support systems, thermal control system, plant trays, lights and other internal outfitting (see figure 4-2). All of these systems are packaged into manageable logistic modules and pallets. The first step in assembly is to clear the area from rocks and to lightly grade the site for the mat foundation. Once the mat foundation is placed into position, the inflatable structure is connected to it and inflated. The inflatable structure is prepackaged with the internal flooring system and the life support distribution and collection system. Then the crew has to perform an EVA in order to fix the cables on the Martian surface by installing the anchoring systems. Once the internal atmosphere is deemed to be safe and the greenhouse is fixed on the Martian surface, a construction crew can complete the internal outfitting. The plant trays, lighting, food processing equipment and internal furniture are brought in and installed. [Kennedy, 1992]

3.9 Power Supply

A source of power will be required for operating the diverse systems on the surface of Mars, including the inflatable greenhouse discussed in this document. A large fixed power source would be required to support the propellant manufacturing facility, the surface habitats and the greenhouse. A mobile source of power would be required to support the rovers that will move the crew and scientific instruments across the surface of Mars. Various power sources were reviewed for their appropriateness to meet the mission requirements and guidelines for the Design Reference Mission (see section 2.1), including solar, nuclear, isotopic, electrochemical, and chemical for both the fixed and mobile power source. [Hoffmann et al., 1997]

To meet the power requirements of the base two power systems were evaluated: the nuclear and the solar power system. The issue to use nuclear power systems to support spaceflight is highly political. While power systems based on nuclear reactors offer the most economical performance, compared to other currently available technologies, especially for systems designed to generate a megawatt or more, only non-nuclear power options are permitted under some mission scenarios. However, from an engineering perspective, nuclear power systems may be essential to provide the required power at an acceptable cost. Solar power systems would require very large and massive arrays to provide adequate power, especially during a Martian dust storm. In addition, it would be very costly and hard to keep them clear of dust. Furthermore, solar power generation would be much worse located away from the equator. Table 3-19 shows estimated costs for the optional power sources. [Hoffmann et al., 1997; Drysdale et al., 1999]

Table 3-19: Cost of Mars Mission Power Options [Drysdale et al., 1999]

POWER OPTIONS	COST [kW/kg]
Solar Photovoltaic Power Generation with Regenerative Fuel Cell Power Storage	0.0057
Nuclear Reactor on a Mobile Cart with Shielding	0.0044
Nuclear Reactor on Lander with Shielding	0.0110
Nuclear Reactor Emplaced in Excavated Hole	0.0190

3.10 In-situ Resource Utilization

Significant quantities of local resources are available on Mars that can be used for an inflatable greenhouse (see section 2.2). These resources, their function and how they may be obtained or produced locally are summarized in table 3-20. Their utilization can lead to reduced launch costs resulting from huge mass savings. The Martian regolith may be used for radiation and meteoroid protection. In addition, it may be used as growth media for the plants if it is proven not to be toxic. Water is one of the key factors of plant growth, even with a high recycling rate it is needed extensively. It could be available from the Martian atmosphere, from permafrost that is expected to be extensive a meter or two below the surface, from polar ice, or from subsurface water or ice deposits. It could also be made from atmospheric carbon dioxide, if a source of hydrogen was available. Even if hydrogen had to be shipped from Earth, this would still give a 5 to 1 cost advantage. The cost of acquisition would depend on the cost of extraction and purification. Currently, the abundance and location of Mars water is undetermined. The atmosphere of Mars contains a minimal quantity of 210 ppm water vapor. It is likely that large deposits of water exist on both Martian poles, but having access to the water is complicated by the seasonal deposition of frozen carbon dioxide on top of the ice deposits. [Drysdale et al., 1999]

Atmospheric carbon dioxide could serve as pressurizing gas for a low pressure greenhouse and could support plant growth, especially if plant growth is proven to be feasible at high CO_2 levels. It is also required when the greenhouse is set up and started remotely. It could be readily extracted from the atmosphere, which contains 95% carbon dioxide, though at a very low pressure. Other options for inert gases to pressurize the greenhouse would be N_2 and Ar. Both are available in small quantities from the Martian atmosphere. Finally, oxygen for crew respiration is needed until the greenhouse operates properly and provides the required amount of oxygen. It can be obtained from the atmosphere, either by removing the rest of the gases, or by reaction with the atmospheric carbon dioxide using either a Sabatier electrolysis or zirconia cell reaction. [Drysdale et al., 1999]

The Design Reference Mission (DRM) proposes to use local resources from the Martian atmosphere in order to make rocket propellant, i.e. liquid methane and oxygen, for the Mars ascent vehicle (see section 2.1). While oxygen is available as a product from splitting carbon dioxide, methane requires a source of hydrogen. Water provides a readily source of hydrogen, but as mentioned before, it may not be readily available. The same chemical plant could be used to extract the required gases for the greenhouse from the Martian atmosphere. [Drysdale et al., 1999; Hoffmann et al., 1997]

Table 3-20: Overview of In-situ Resource Utilization Options [Drysdale et al., 1999]

RESOURCE	FUNCTION	ACQUISITION
Regolith	- radiation and meteoroid protection - growth media	-moving and crushing
Water	- huge amounts necessary for plant growth	- extraction from local atmosphere, permafrost, polar ice, surface water or ice deposits - made from hydrogen (obtained by electrolysis of local water or shipped from Earth) and atmospheric carbon dioxide
Carbon dioxide	- essential gas for photosynthesis - pressurizing gas for greenhouse atmosphere	- extraction from local atmosphere
Nitrogen Argon	- pressurizing gas for greenhouse atmosphere	- extraction from local atmosphere
Oxygen	- crew respiration	- electrolysis of local water - extraction from local atmosphere
Methane Liquid oxygen	- rocket propellant	- made from hydrogen (obtained by electrolysis of local water or shipped from Earth) - splitting of carbon dioxide

4 Mars Greenhouse Design-Trade Studies

A Mars surface greenhouse can be realized in different designs. For example, it can be built as an inflatable module or as a solid structure. Furthermore, it has to be investigated whether transparent or opaque material is economic in terms of mass and power required by the selected method of lighting (artificial, solar, hybrid). This decision also affects the shielding technique for the greenhouse. The minimum pressure requirements of the plants have to be studied as low pressure can result in lighter structures possibly leading to significant mass savings. On the other hand, if a low pressure (30 kPa) greenhouse is chosen, pre-breathing is required for the astronauts in order to avoid decompression problems. The greenhouse design trades that have to be made are summarized in table 4-1. In this document the focus has been on the structures, materials and thermal aspects. Figure 4-1 gives the flow diagram of the Mars surface greenhouse design trades.

Table 4-1: Mars Surface Greenhouse Trades

CRITERIA	TRADEOFF
Structure	solid structure vs. inflatable
Material	Transparent vs. opaque
Method of lighting	solar vs. artificial vs. hybrid
Operational pressure	high (60 kPa) vs. low (30 kPa) pressure
Shielding	regolith vs. water bladder vs. more layers
Servicing and harvesting	crew vs. robots
Resupply	low food closure level vs. high closure
Plant trays	one level vs. more levels

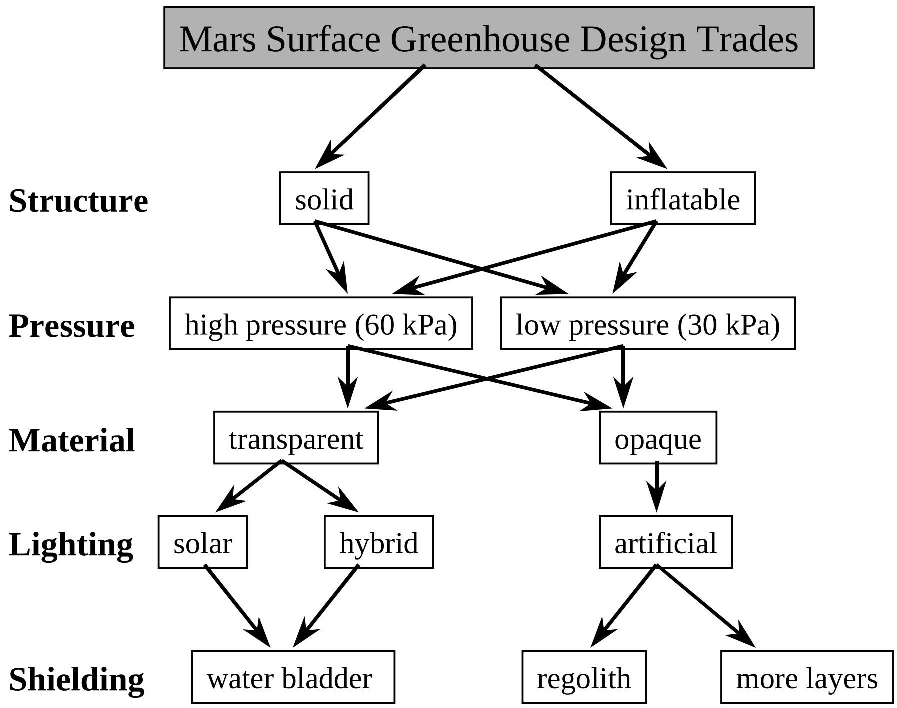


Figure 4-1: Flow Diagram for the Mars Surface Greenhouse Design Trades

There are numerous requirements impacting the greenhouse design process. The greenhouse has to provide: [Kennedy, 1999]

- Required growth area
- Secondary structure to support equipment and plant growth system
- Environmental control and life support system
- Communications (human to human, human to machine)
- Command and data handling
- Transition space (airlock) for crew and equipment into greenhouse
- Lighting (natural or artificial)
- External structural interfaces to other pressurized modules
- External power interface to power supply or other pressurized modules
- External data interface to data supply or other pressurized modules
- External thermal interface to thermal supply and/or other pressurized modules
- External gaseous interface to other pressurized modules
- External wastewater interface to wastewater return and/or other pressurized modules
- External communication (audio/video) interface to other pressurized modules
- Robotic system interfaces (e.g. grapple fixture, etc.)
- Integrated subsystems
- Easy deployment and assembly
- Radiation protection
- Micrometeoroid and/or dust storm protection

4.1 Design Criteria

According to figure 4-1 various greenhouse designs are possible. In order to compare their feasibility, design criteria have to be defined. These design criteria can be categorized into five classifications as summarized in table 4-2: [Drake, 2000]

- **Performance**
  It has to be analyzed if the greenhouse architecture supports multiple missions rather than a one-time mission and if it can be applied to multiple destinations, i.e., also to the Moon. Furthermore, the greenhouse should accommodate modifications of mission requirements, i.e., if for example the number of crew members varies or the surface stay time is changed. In addition, the greenhouse architecture should be flexible to changes in subsequent missions. The number of launches required to build the greenhouse and to support it should also be considered.
- **Safety**
  Possible situations that may lead to demolition of the greenhouse have to be evaluated. The levels of redundancy within the systems of the greenhouse should be analyzed. The significance of hazards arising from the systems and the materials have to be evaluated. The crew exposition to radiation and the crew-time requirement should be minimized.
- **Technology**
  It has to be analyzed whether the greenhouse is dependent on specific technologies and the current maturity level of these technologies.
- **Schedule**
  The necessary time for development of the required technologies and systems have to support the planned launch date.

- **Cost**

The technology readiness level of the required technologies should be evaluated. It has to be analyzed whether the required systems are simple or complex. The initial and yearly resupply mass as well as the power and crew-time requirements should be considered as cost drivers. The recurring and not-recurring costs have to be calculated. It has to be analyzed whether the costs can be shared with other programs or not.

Table 4-2: Mars Surface Greenhouse Design Criteria [Drake, 2000]

CRITERIA	WEIGHT	KEY QUESTION	FACTORS
Performance	10%	Which architecture provides the most flexibility for meeting future human exploration and development of space needs?	• Strategic Objectives • Mission Objectives • Number of Launches
Safety	30%	Which architecture best ensures crew safety and productivity for all mission phases?	• Abort Scenarios • Redundancy • Hazards • Crew Issues
Technology	25%	Does one architecture have significantly higher risk?	• Architecture Sensitivity • Technology Maturity • Risk Mitigation
Schedule	5%	Does one architecture need to start design and development activities significantly earlier?	• Technology Development • System Development & Integration • Mission/Launch Processing
Cost	30%	Which architecture is expected to provide lower initial and/or total life cost?	• Technology • Systems • Recurring Costs • Non-recurring Cost • Cost sharing Potential

4.2 Structures and Materials

The inflatable greenhouse discussed in this document is a horizontally orientated semi-cylindrical air-inflated pneumatical structure depicted in figure 4-2. All edges are rounded in order to avoid high stresses in the structure. The end is shaped as a quarter of a sphere. This space can be used for storage of equipment, crops, regenerative life support systems and the thermal control system. Additional storage space is available under the plant trays. The root zone is assumed to be 10 cm and the free space used for plant growth above the plant trays has to be at least 1.0 m. As an example the interior design of a greenhouse with a growth area of 90 m^2 and a diameter of 4.9 m (see table 4-3) is given in figure 4-3. A floor scuff has to be used to avoid the damage of the bladder and restraint layer. The individual greenhouses will be connected by a tunnel (similar to the BIO-Plex project, see section 3.1.3). The number of greenhouses connected to this tunnel depends on the amount of required in-situ food production. The greenhouse will be tied to the Martian surface by a web of cables in order to avoid that the greenhouse pops up due to its internal pressure. The cables are fixed on the

Martian surface by an anchoring system. This concept is depicted in figure 4-4. [Kennedy, 2000; Heyne, 1999]

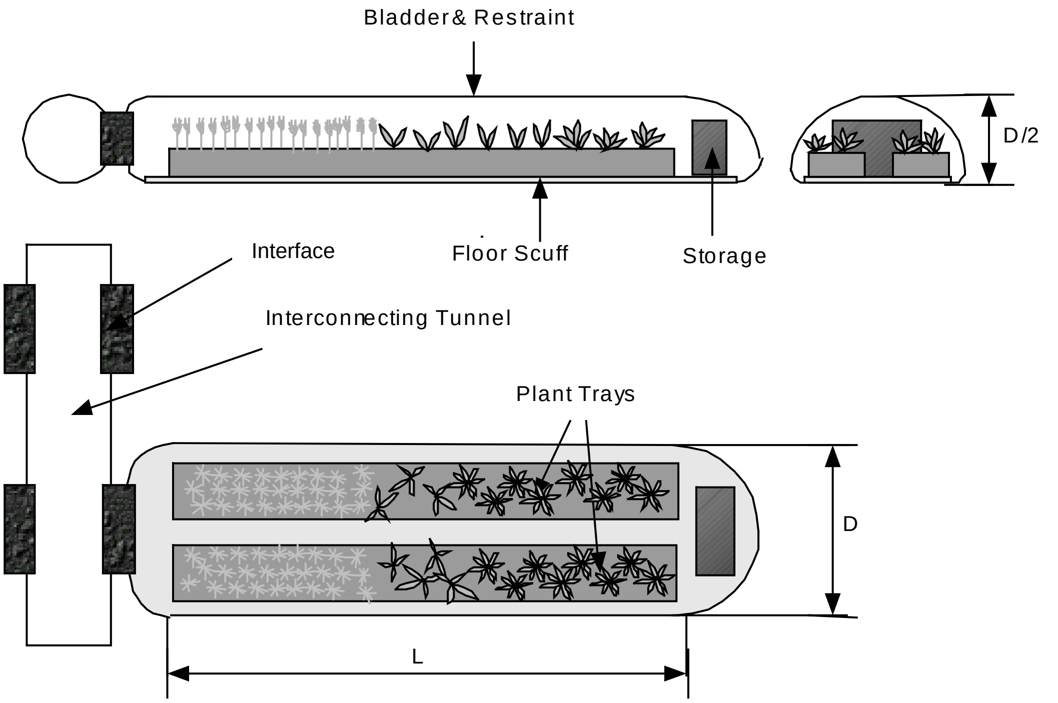


Figure 4-2: Greenhouse Design Overview

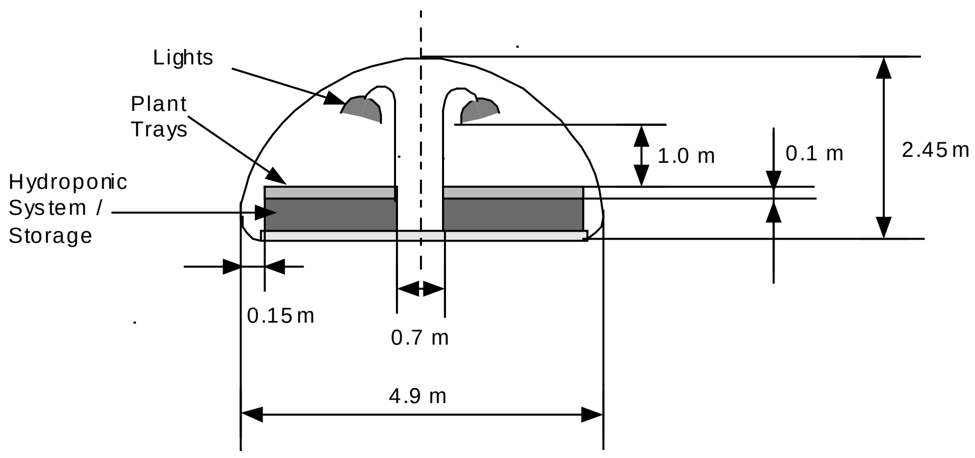


Figure 4-3: Interior Design of a Greenhouse for a Required Growth Area of 90 m^2

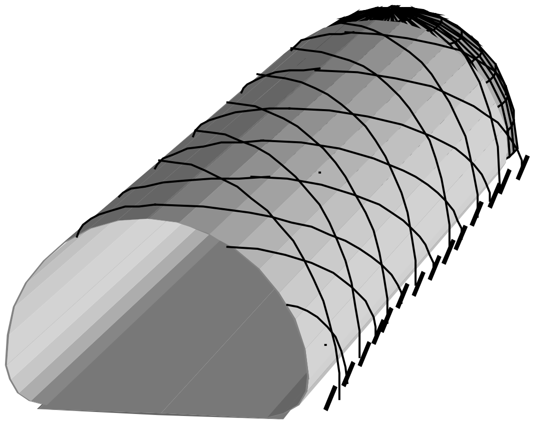


Figure 4-4: Greenhouse Cable and Anchoring System

4.2.1 Greenhouse with Natural Lighting

Given the geometry of the greenhouse and the mass of the surface material per area, the mass of the primary structure can be calculated. The goal is to minimize the mass that is required per growth area. This can be achieved by minimizing the surface area of the greenhouse according to equation 4-1. The surface area of the greenhouse can be calculated with equation 4-2. In order to find the minimum surface area depending on the greenhouse geometry the derivation (see equation 4-3) has to be formed. This equation is equal to zero for the design parameters that minimize the greenhouse surface. If, e.g., a growth area of 90 m^2 is chosen the mass per growth area is minimal at a length-diameter relation of 4.75 (see figure 4-5).

$$m_{Greenh.} = A_{Surface} \, [(m/A_{Surface})_{Bladder} + (m/A_{Surface})_{Restraint}] \qquad \text{(equ. 4-1)}$$

$$A_{Surface} = A_{Hull} + A_{Floor} - A_{Hatch} \qquad \text{(equ. 4-2)}$$

$$= [\tfrac{1}{2} D \pi L + (D/2)^2 \pi + [\tfrac{1}{2} (D/2)^2 \pi]] + [D L + \tfrac{1}{2} (D/2)^2 \pi] - [(0.81m)^2]$$

$$= \tfrac{1}{2} (A_{Grow} \pi + L \pi s) + (A_{Grow} + L s) + \tfrac{1}{2} (A_{Grow}/L + s)^2 \pi - (0.81m)^2$$

where:

D = Greenhouse Diameter = $A_{Grow}/L + s$
L = Greenhouse Length
$A_{Surface}$ = Surface of Greenhouse
A_{Hull} = Hull of Greenhouse
A_{Floor} = Floor Area of Greenhouse
A_{Hatch} = Area of Hatch (assumed to be a square of $[0.81m]^2$)
A_{Grow} = Growth Area for Plants
s = Clearance Space between Plant Trays (assumed to be 1 m)

$$(dA_{Surface}/dL)_{A_{grow} = const} = 1/L^3 \, [\tfrac{1}{2} \pi s L^3 + s L^3 + A_{grow}^2 \pi - A_{grow} L \pi s] = 0 \qquad \text{(equ. 4-3)}$$

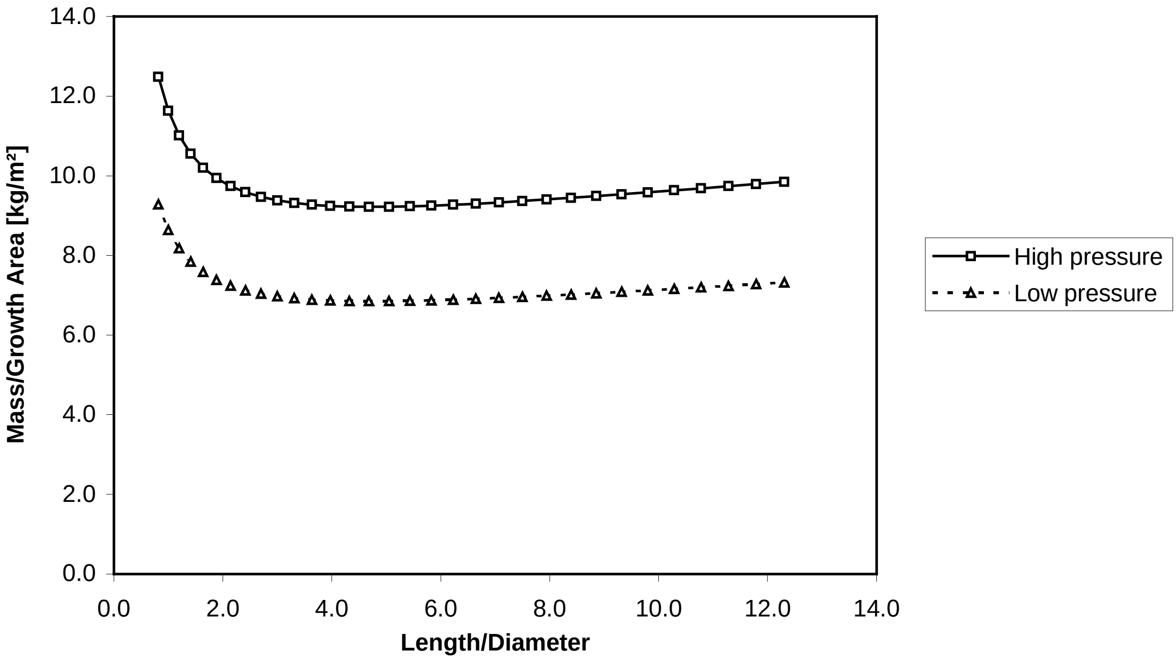


Figure 4-5: Optimization of Length-Diameter Relation for Constant Growth Area of 90 m^2 (Natural Lighting)

As shown above, the optimal greenhouse length-diameter relation can be calculated for various growth areas. The properties of greenhouses depending on the required growth area are listed in table 4-3. If, e.g., a growth area of 90 m^2 was required, the primary structure would have a mass of 829.8 kg for a greenhouse operated at high pressure (60 kPa), 616.6 kg for a greenhouse operated at low pressure (30 kPa). This results in a mass per growth area relation of 9.22 kg/m^2 for high pressure and 6.85 kg/m^2 for low pressure.

According to figure 4-6, the optimal length-diameter relation increases with increasing required growth area, i.e., the greenhouse's length has to be approximately four to five times longer than the diameter for a growth area between 50 and 120 m^2. The mass per growth area decreases with the increasing growth area. Consequently, the larger the growth area is foreseen in one greenhouse the lower is the mass requirement. A mass saving of 26% can be achieved for the primary structure by operating the greenhouse at low pressure (30 kPa) compared to a high pressure greenhouse (60 kPa).

Table 4-3: Properties of a Greenhouse Depending on the Required Growth Area (Natural Lighting)

Growth Area [m²]	A_{grow}	**50.00**	**60.00**	**70.00**	**80.00**	**90.00**	**100.00**	**110.00**	**120.00**
Length [m]	L	15.91	17.88	19.73	21.49	23.18	24.80	26.37	27.89
Diameter [m]	D	4.14	4.36	4.55	4.72	4.88	5.03	5.17	5.30
Length/Diameter	L/D	3.84	4.10	4.34	4.55	4.75	4.93	5.10	5.26
Upper Surface [m²]	$A_{surf, Hull}$	123.23	144.19	164.84	185.24	205.44	225.46	245.33	265.06
Floor Surface [m²]	$A_{surf, Floor}$	72.66	85.34	97.86	110.26	122.55	134.76	146.88	158.94
Volume [m³]	V	125.97	155.01	185.08	216.03	247.76	280.29	313.49	347.37
Bladder Mass [kg/m²]	$m_{Bladder}/A_{surf}$	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Restraint Mass (high pressure) [kg/m²]	$m_{Restr,high}/A_{surface}$	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Restraint Mass (low pressure) [kg/m²]	$m_{Restr,low}/A_{surface}$	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Mass (high pressure) [kg]	$m_{Gh, high}$	495.59	580.70	664.63	747.61	829.81	911.34	992.29	1072.74
Mass (low pressure) [kg]	$m_{Gh, low}$	368.26	431.50	493.87	555.54	616.62	677.20	737.35	797.13
Mass/Growth area (high pressure) [kg/m2]	$m_{Gh, high}/A_{grow}$	9.91	9.68	9.49	9.35	9.22	9.11	9.02	8.94
Mass/Growth area (low pressure) [kg/m2]	$m_{Gh, low}/A_{grow}$	7.37	7.19	7.06	6.94	6.85	6.77	6.70	6.64
Ratio Mass (low/high pressure)	$m_{Gh, low}/m_{Gh, high}$	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74

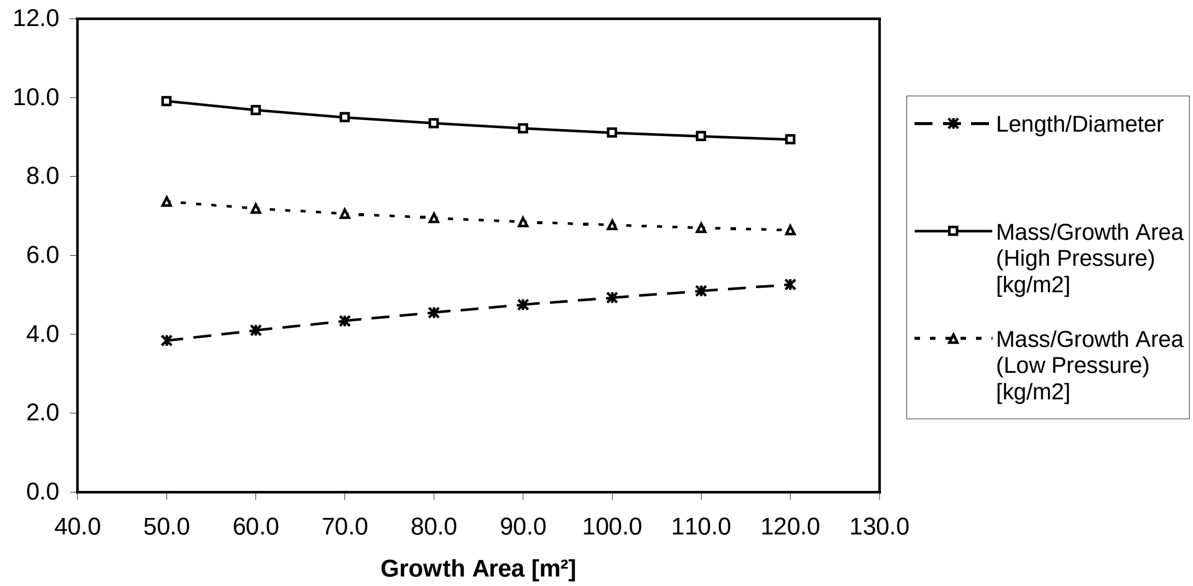


Figure 4-6: Mass per Growth Area for Varying Growth Areas (Natural Lighting)

4.2.2 Greenhouse with Artificial Lighting

For an inflatable greenhouse using artificial lighting an opaque multi-layer insulation (MLI) envelops the bladder and restraint layer (see figure 3-13) in order to avoid the immense heat loss during the night. The mass of the MLI has to be considered for the calculation of the primary structure mass (see equation 4-4). According to the equations 4-2 and 4-3, the mass can be limited by limiting the surface area. An example of the mass per growth area relation varying with the geometrical design parameters for a growth area of 90 m^2 is given in figure 4-7.

$$m_{Greenh.} = A_{Surface}\,[(m/A_{Surface})_{Bladder} + (m/A_{Surface})_{Restraint} + (m/A_{Surface})_{MLI}] \qquad \text{(equ.4-4)}$$

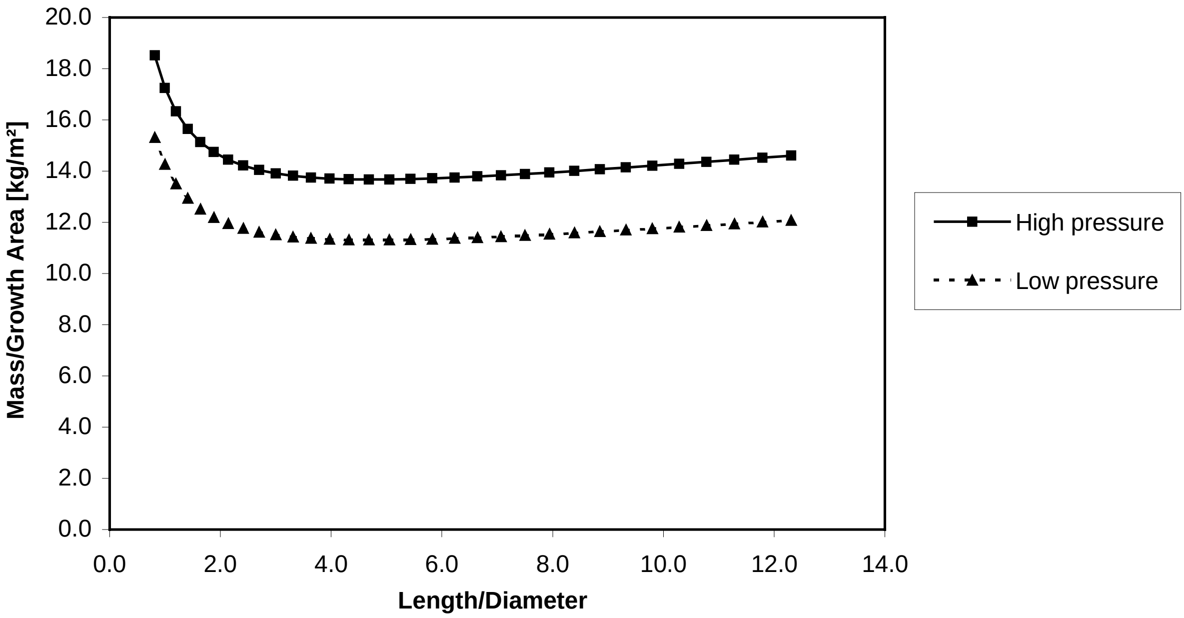


Figure 4-7: Optimization of Length-Diameter Relation for Constant Growth Area (90 m^2) (Artificial Lighting)

Table 4-4 and figure 4-8 show the relevant greenhouse design parameters depending on the required growth area. If artificial lighting is chosen the mass of the primary structure can be reduced by 17%, if low pressure (30 kPa) instead of high pressure (60 kPa) is chosen.

Table 4-4: Properties of a Greenhouse Depending on the Required Growth Area (Artificial Lighting)

Growth Area [m²]	A_{grow}	**50.00**	**60.00**	**70.00**	**80.00**	**90.00**	**100.00**	**110.00**	**120.00**
Length [m]	L	15.91	17.88	19.73	21.49	23.18	24.80	26.37	27.89
Diameter [m]	D	4.14	4.36	4.55	4.72	4.88	5.03	5.17	5.30
Length/Diameter	L/D	3.84	4.10	4.34	4.55	4.75	4.93	5.10	5.26
Upper Surface [m²]	$A_{surf, Hull}$	123.23	144.19	164.84	185.24	205.44	225.46	245.33	265.06
Floor Surface [m²]	$A_{surf, Floor}$	72.66	85.34	97.86	110.26	122.55	134.76	146.88	158.94
Volume [m³]	V	125.97	155.01	185.08	216.03	247.76	280.29	313.49	347.37
Bladder Mass [kg/m²]	$m_{Bladder}/A_{surf}$	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Restraint Mass (high pressure) [kg/m²]	$m_{Restr,high}/A_{surface}$	1.31	1.31	1.31	1.31	1.31	1.31	1.31	1.31
Restraint Mass (low pressure) [kg/m²]	$m_{Restr,low}/A_{surface}$	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
MLI Mass [kg/m²]	$m_{MLI}/A_{surface}$	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Mass (high pressure) [kg]	$m_{Gh, high}$	734.6	860.7	985.1	1108.1	1230.0	1350.8	1470.8	1590.0
Mass (low pressure) [kg]	$m_{Gh, low}$	607.2	711.5	814.4	916.1	1016.8	1116.7	1215.9	1314.4
Mass/Growth area (high pressure) [kg/m²]	$m_{Gh, high}/A_{grow}$	14.69	14.35	14.07	13.85	13.67	13.51	13.37	13.25
Mass/Growth area (low pressure) [kg/m²]	$m_{Gh, low}/A_{grow}$	12.14	11.86	11.63	11.45	11.30	11.17	11.05	10.95
Ratio Mass (low/high pressure)	$m_{Gh, low}/m_{Gh, high}$	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83

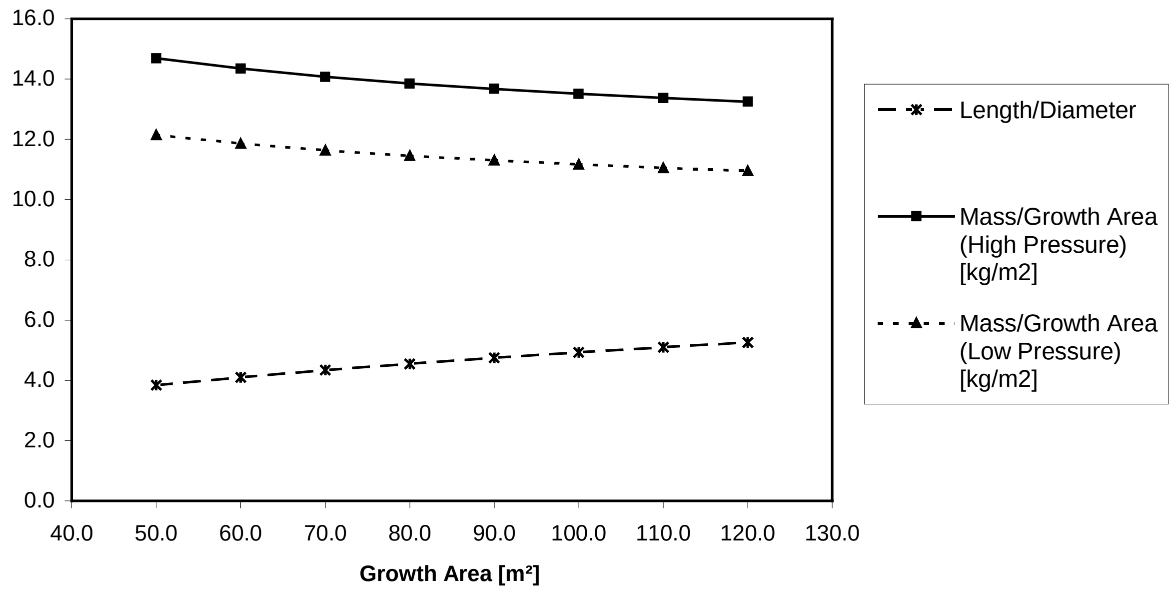


Figure 4-8: Mass per Growth Area for Varying Growth Areas (Artificial Lighting)

The following four cases prior analyzed in this section can be compared:

- High pressure (60 kPa) greenhouse using artificial lighting
- Low pressure (30 kPa) greenhouse using artificial lighting
- High pressure (60 kPa) greenhouse using natural/hybrid lighting
- Low pressure (30 kPa) greenhouse using natural/hybrid lighting

The mass savings are depicted in figure 4-9. If the greenhouse is operated with low pressure (30 kPa) instead of high pressure (60 kPa) the mass can be reduced to 82.6% for artificial lighting and to 74.3% for natural/hybrid lighting. The change of the lighting method from artificial to natural/hybrid lighting would reduce the mass to 67.5% for a high pressure greenhouse and 60.7% for a low pressure greenhouse. The mass of the primary structure of a low pressure greenhouse using natural/hybrid lighting is only 50.1% of a high pressure greenhouse using artificial lighting.

Figure 4-10 shows the mass per growth area for those four cases depending on the required growth area, the lighting method and the pressure. With equation 4-4 the mass for a high pressure greenhouse using artificial lighting can be calculated. This result can be transformed with a relevant factor into the other three cases using equation 4-5.

$$m/A_{grow} = (m/A_{Grow})_{art.,high} \times f \qquad \text{(equ. 4-5)}$$

where :

$f_{art,\ high} = 100.0\%$
$f_{art,\ low} = 82.6\%$
$f_{nat/hyb,\ high} = 67.5\%$
$f_{nat/hyb,\ low} = 50.1\%$

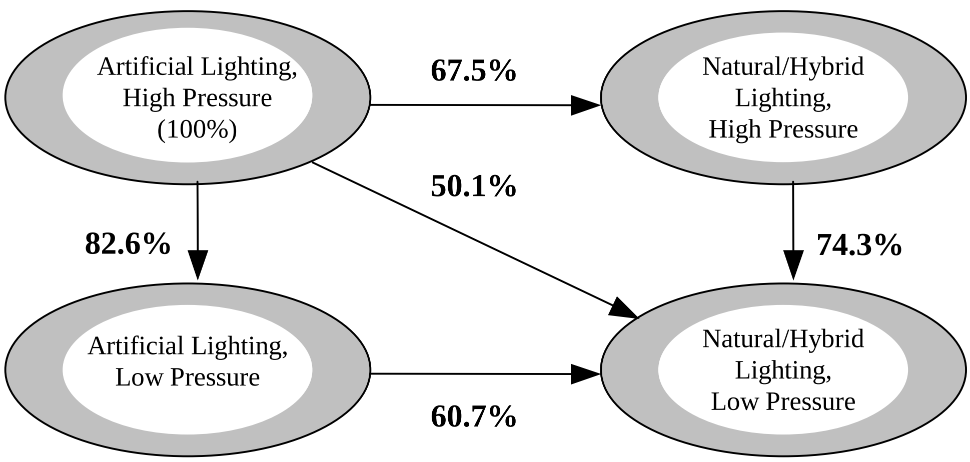


Figure 4-9: Mass Savings depending on Lighting Method and Pressure Level

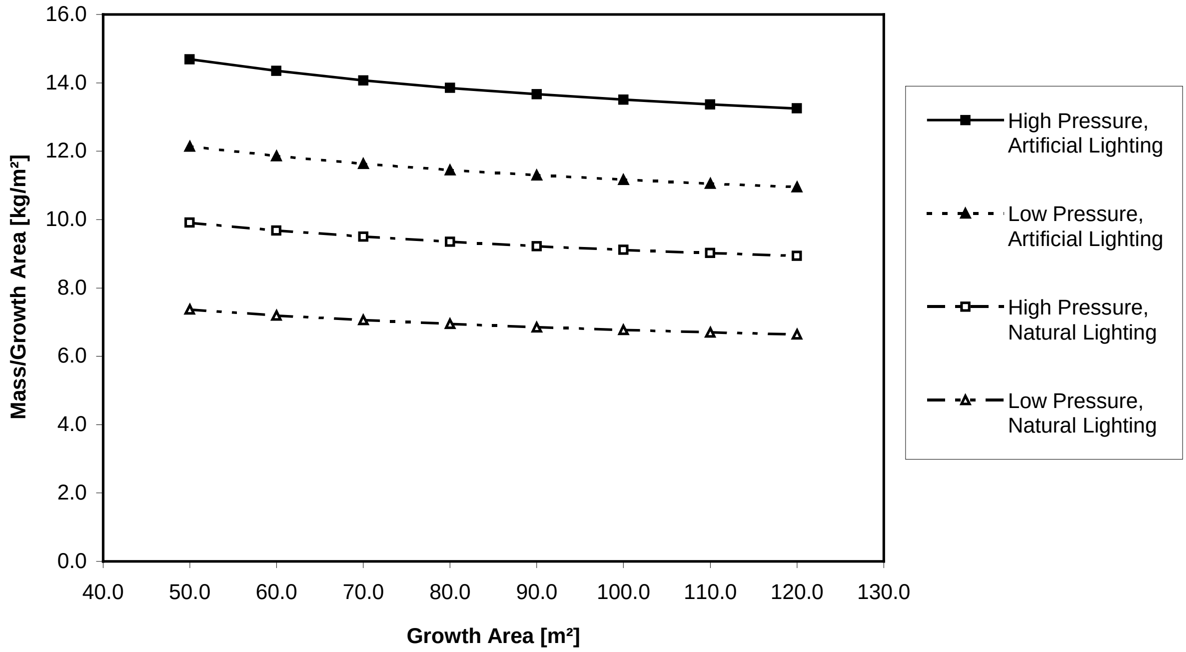


Figure 4-10: Comparison of Mass per Growth Area depending on Growth Area, Lighting Method and Pressure Level

4.3 Thermal Control System

4.3.1 Greenhouse with Natural Lighting

With the Stefan-Boltzmann relation (see section 3.4.1) the **cooling and heating requirements** for a transparent greenhouse are calculated by comparing the solar heat income to the heat loss by radiation according to the following assumptions: [Schwarzkopf, 1990]

- Greenhouse shielded from view of the proximal Martian surface to prevent heating by sunlight reflected from surface.
- Heat transfer by conduction through the greenhouse floor is 0, due to insulation ability of Martian regolith.
- Greenhouse covering transmittance is:
  τ = 0.65 (low pressure [30 kPa] greenhouse),
  τ = 0.55 (high pressure [60 kPa] greenhouse).
- Emissivity of the greenhouse surface is 1.0 for the heating requirement calculation and 0.8 for the cooling requirement calculation.
- Diurnal temperature range on Mars: 187 - 242 K (data of Viking 1 landing site [22° north latitude] during mid-summer).

Solar heat gain/loss during Martian day is calculated to be: [Schwarzkopf, 1990]

$$Q_s = I_{dn}\ \tau\ A_{in} - \varepsilon\ b\ (T_i^4 - T_s^4)\ A_{out} \quad \text{(equ. 4-6)}$$

where:

Q_s = solar heat gain/loss (W)
I_{dn} = incident direct normal solar radiation per unit area (590 W/ m^2)
τ = transmittance (0.55 [high pressure], 0.65 [low pressure])

ε = emissivity (0.8)
b = Stefan-Boltzmann constant (5.67×10^{-8} W/[$m^2 \times K^4$])
T_i = interior temperature (assumed to be 298 K)
T_s = Mars environment temperature (187 - 242 K: Viking 1 landing site data)
A_{in} = projected floor area
A_{out} = greenhouse hull area (hatch area excluded)

Given the geometry of the greenhouse (see section 4-2) equation 4-6 can be further developed. Equation 4-7 shows the solar heat gain, depending on the geometry and the thermal properties of the greenhouse.

$$Q_s = I_{dn}\,\tau\,A_{in} - \varepsilon\,b\,(T_i^4 - T_s^4)\,A_{out}$$
$$= I_{dn}\,\tau\,([D\,L + ½\,(D/2)^2\,\pi]\,\sin\alpha)_{in} - \varepsilon\,b\,(T_i^4 - T_s^4)\,(½\,D\,\pi\,L + (D/2)^2\,\pi + [½\,(D/2)^2\,\pi] - [(0.81m)^2]\,)_{out} \quad \text{(equ. 4-7)}$$

where:
A_{in} = $A_{Floor}\sin\alpha$ = $[D\,L + ½\,(D/2)^2\,\pi]\sin\alpha$
A_{out} = $A_{Hull} - A_{Hatch}$ = $[½\,D\,\pi\,L + (D/2)^2\,\pi + [½\,(D/2)^2\,\pi] - [(0.81m)^2]$
α = angle of sun relative to greenhouse horizontal (assuming 12 hours of Martian night [18 - 6 local solar time] and 12 hours of Martian day [6-18 local solar time], sun at zenith at noon)

Heating requirement during Martian night is calculated to be: [Schwarzkopf, 1990]

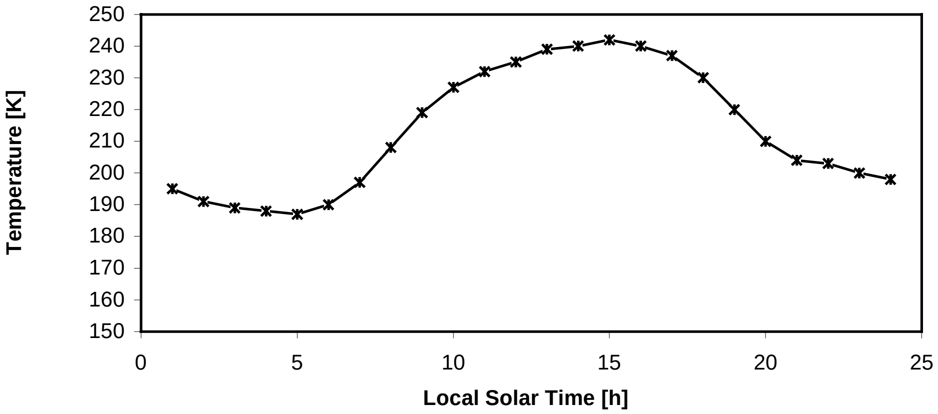
$$Q_e = \varepsilon\,b\,(T_i^4 - T_s^4)\,A_{out} \quad \text{(equ. 4-8)}$$

where:
Q_e = total heating requirement (W)
ε = emissivity (1.0)
b = Stefan-Boltzmann constant (5.67×10^{-8} W/[$m^2 \times K^4$])
T_i = interior temperature (assumed to be 298 K)
T_s = Mars environment temperature (187 - 242 K: Viking 1 landing site data)
A_{out} = greenhouse hull area (hatch area excluded)

$$Q_s = \varepsilon\,b\,(T_i^4 - T_s^4)\,A_{out}$$
$$= \varepsilon\,b\,(T_i^4 - T_s^4)\,([½\,D\,\pi\,L + (D/2)^2\,\pi + [½\,(D/2)^2\,\pi] - [(0.81m)^2]\,)_{out} \quad \text{(equ. 4-9)}$$

where:
A_{out} = $A_{Hull} - A_{Hatch}$ = $[½\,D\,\pi\,L + (D/2)^2\,\pi + [½\,(D/2)^2\,\pi] - [(0.81m)^2]$

The heat gain during the day and the heat loss during the night can be calculated with the equations 4-7 and 4-9 by knowing the diurnal temperature cycle and the diurnal solar radiation. As an example the diurnal temperature data of the Viking 1 lander site is chosen (see figure 4-11). The calculation of the solar heat gain during the Martian day shows that the maximum heat gain is at one hour local solar time due to the peak of the solar radiation at noon, when the sun is at the zenith, even if the maximum temperature is at 15 hours local solar time (see figure 4-12). In table 4-5 the minimum, maximum and average solar heat gain/loss of a high pressure (60 kPa) greenhouse is compared to a low pressure (30 kPa) greenhouse. The high pressure greenhouse loses heat during the complete diurnal temperature cycle, the low pressure greenhouse gains heat for a short period of time around noon as the transmittance of the high pressure greenhouse is lower compared to the low pressure



greenhouse (see section 3.4).

Figure 4-11: Daily Diurnal Temperature Cycle at Viking 1 Landing Site (22° North Latitude) during Mid-summer [Rapp, 1997]

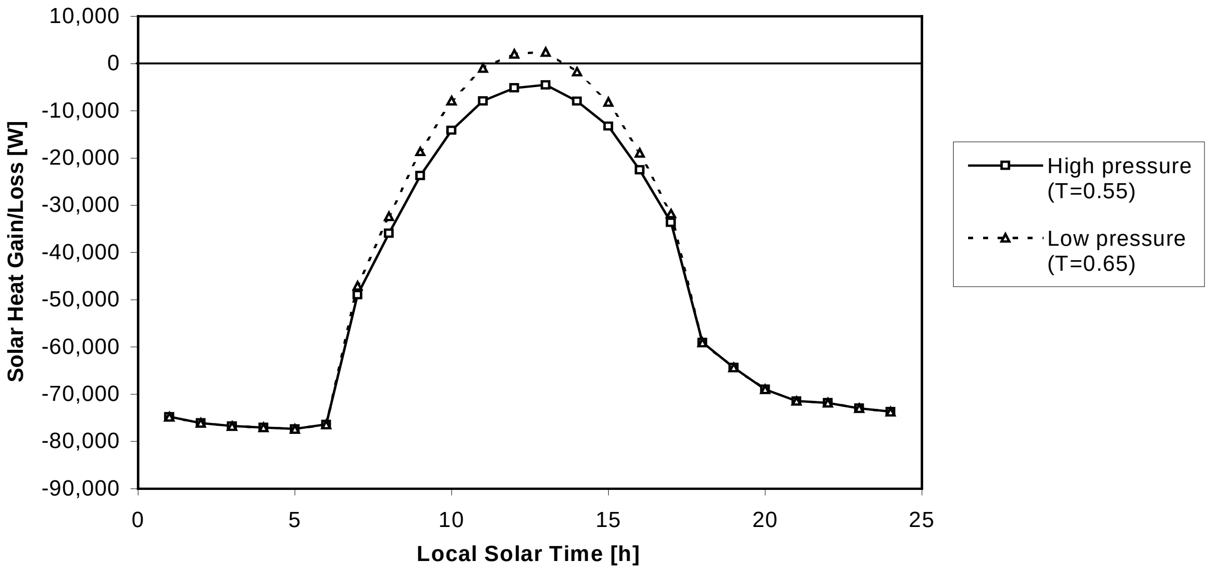


Figure 4-12: Solar Heat Gain/Loss for a Low and a High Pressure Transparent Greenhouse (Growth Area = 90 m^2) at Viking 1 Landing Site during Mid-summer

Table 4-5: Min./Max./Average Solar Heat Gain/Loss for a Low and a High Pressure Transparent Greenhouse (90 m^2 Growth Area) at Viking 1 Landing Site during Mid-summer

	HIGH PRESSURE (60 kPa)	**LOW PRESSURE (30 kPa)**
Min. Solar Heat Gain/Loss [kW]	-77.4	-77.4
Max. Solar Heat Gain/Loss [kW]	-4.5	2.5
Average Solar Heat Gain/Loss [kW]	-48.3	-46.0

Furthermore, it should be analyzed which greenhouse is more economic in terms of heat/gain loss per growth area. Figure 4-13 indicates that a greenhouse with a lower growth area loses significantly more heat than a greenhouse with a higher growth area. The heat gain around the Martian noon is almost independent of the growth area, with a slightly higher heat gain for the greenhouses comprising higher growth areas. The minimum, maximum and average heat gain/loss per growth area for greenhouses with varying growth areas are listed in table 4-6.

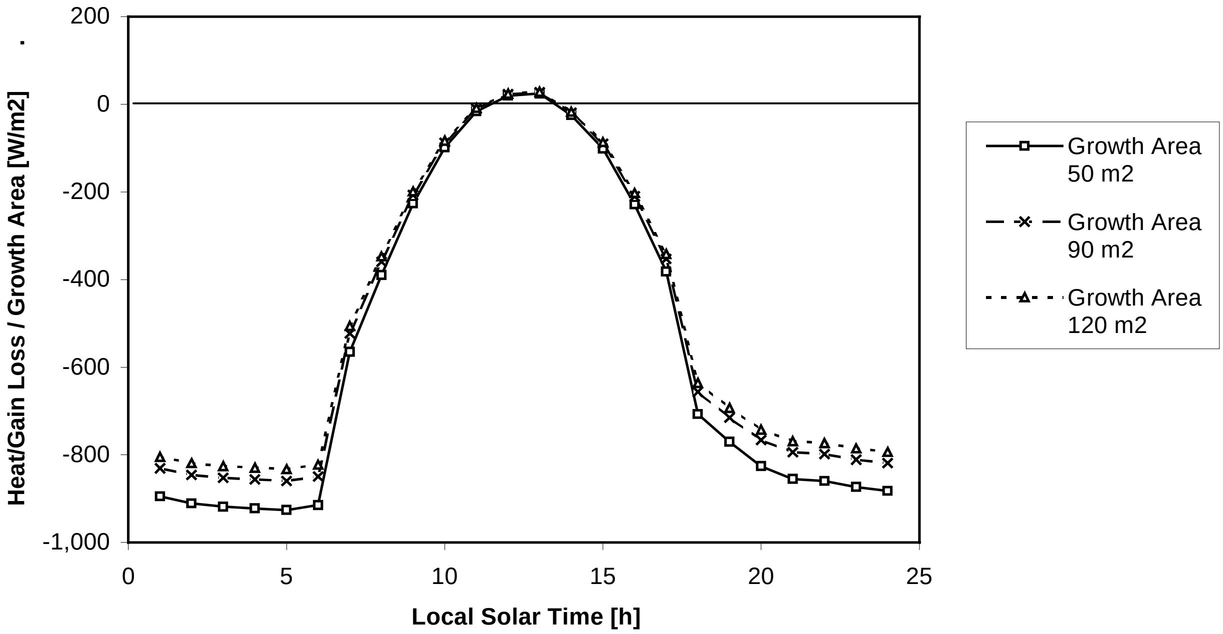


Figure 4-13: Solar Heat Gain/Loss per Growth Area for a Low Pressure Transparent Greenhouse with Varying Growth Areas at Viking 1 Landing Site during Mid-summer

Table 4-6: Min./Max./Average Solar Heat Gain/Loss per Growth Area for a Low Pressure Transparent Greenhouse with Varying Growth Areas at Viking 1 Landing Site during Mid-summer

GROWTH AREA [m^2]	**50**	**90**	**120**
Min. Solar Heat Gain/Loss per Growth Area [W/m^2]	-926.0	-859.7	-832.6
Max. Solar Heat Gain/Loss per Growth Area [W/m^2]	24.5	27.2	28.6
Average Solar Heat Gain/Loss per Growth Area [W/m^2]	-552.1	-511.1	-494.3

An option to avoid the immense heat loss during the Martian night would be to cover the greenhouse with a multi-layer insulation (MLI). The heat/gain loss is calculated as shown above, only the emissivity during the night has to be changed from 1.0 to 0.05. This results in power savings as the heating requirement decreases. On the other side, the additional mass of the MLI has to be considered for the calculation of the overall mass. Figure 4-14 shows the solar heat gain/loss for a low and a high pressure transparent greenhouse covered with a MLI at night. The minimum, maximum and average heat gain/loss for those greenhouses are listed in table 4-7.

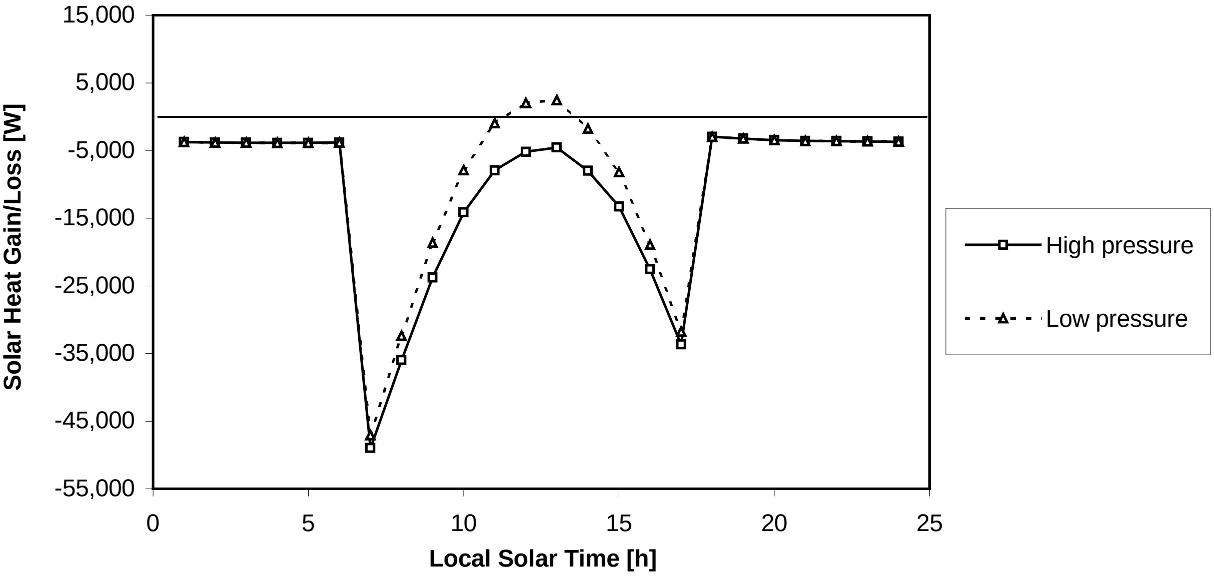


Figure 4-14: Solar Heat Gain/Loss for a Low and a High Pressure Transparent Greenhouse covered with a Multi-layer Insulation at Night (90 m^2 Growth Area) at Viking 1 Landing Site during Mid-summer

Table 4-7: Min./Max./Average Solar Heat Gain/Loss for a Low and a High Pressure Transparent Greenhouse covered with a Multi-layer Insulation at Night (90 m^2 Growth Area) at Viking 1 Landing Site during Mid-summer

	HIGH PRESSURE (60 kPa)	**LOW PRESSURE (30 kPa)**
Min. Solar Heat Gain/Loss [kW]	-49.0	-47.1
Max. Solar Heat Gain/Loss [kW]	-3.0	2.4
Average Solar Heat Gain/Loss [kW]	-11.0	-8.8

4.3.2 Greenhouse with Artificial Lighting

The **heat gain/loss** during the Martian day/night for a greenhouse with an opaque surface material, using artificial lighting, is calculated with equation 4-10 according to similar assumptions as listed in section 4.3.1, except of the greenhouses covering transmittance which is equal to zero as the material is opaque. In addition, the waste heat of the lamps has to be considered as an internal heat source. The assumptions are the following:

- Greenhouse shielded from view of the proximal Martian surface to prevent heating by sunlight reflected from surface.
- Heat transfer by conduction through the greenhouse floor is 0, due to insulation ability of Martian regolith.
- Greenhouse covering transmittance is $\tau = 0$ (high/low pressure greenhouse).
- Lighting level: 1000 µmol/(m^2s), 12 hour lighting period during Martian day (6-18 local solar time).

- Emissivity of the greenhouse surface is 0.05 for the heating and cooling requirement calculation.
- Diurnal temperature range on Mars: 187 - 242 K (data of Viking 1 landing site [22° north latitude] during mid-summer).

$$Q_s = I_{dn}\ \tau\ A_{in} - \varepsilon\ b\ (T_i^4 - T_s^4)\ A_{out} + Q_L = -\ \varepsilon\ b\ (T_i^4 - T_s^4)\ A_{out} + Q_L$$
$$= -\ \varepsilon\ b\ (T_i^4 - T_s^4)\ ([½\ D\ \pi\ L + (D/2)^2\ \pi + [½\ (D/2)^2\ \pi] - [(0.81m)^2]\ )_{out} + Q_L$$

(equ. 4-10)

where:

Q_s = heat gain/loss (W)
Q_L = waste heat lamps (see equation 4-11)
I_{dn} = incident direct normal solar radiation per unit area (590 W/ m^2)
τ = transmittance (0)
ε = emissivity (0.05)
b = Stefan-Boltzmann constant (5.67 x 10^{-8} W/[m^2 x K^4])
T_i = interior temperature (assumed to be 298 K)
T_s = Mars environment temperature (187 - 242 K: Viking 1 landing site data)
A_{in} = projected floor area
A_{out} = greenhouse hull area (hatch area excluded)

High pressure sodium lights are assumed to be used as they are highly efficient (see section 3.3.3). According to the values of table 3-16 their waste heat (approximately power requirement) is the following:

$$Q_L = A_{grow}\ (Q_{P,L} + Q_{B,L}\ )\ (N_{Lamp}/A_{grow}) \quad \text{(equ. 4-11)}$$

where:

A_{grow} = required growth area (m^2)
$Q_{P,L}$ = power requirement per lamp (400 W)
$Q_{B,L}$ = ballast power requirement per lamp (60 W)
(N_L/A_{grow}) = lamps per growth area for a lighting level of 1000 μmol/(m^2s) (5.1 m^{-2})

If, e.g., a growth area of 90 m^2 was required the lamps would produce a waste heat of 211.1 kW. This value has to be added to the natural heat loss by emission. Figure 4-15 shows the diurnal heat loss by emission if the lights would not be turned on. Figure 4-16 shows the total heat gain/loss of the inflatable greenhouse for a 12 hour lighting period from 6 to 18 hours local solar time. Table 4-8 summarizes the minimum, maximum and average heat gain/loss for an inflatable opaque greenhouse with and without lighting.

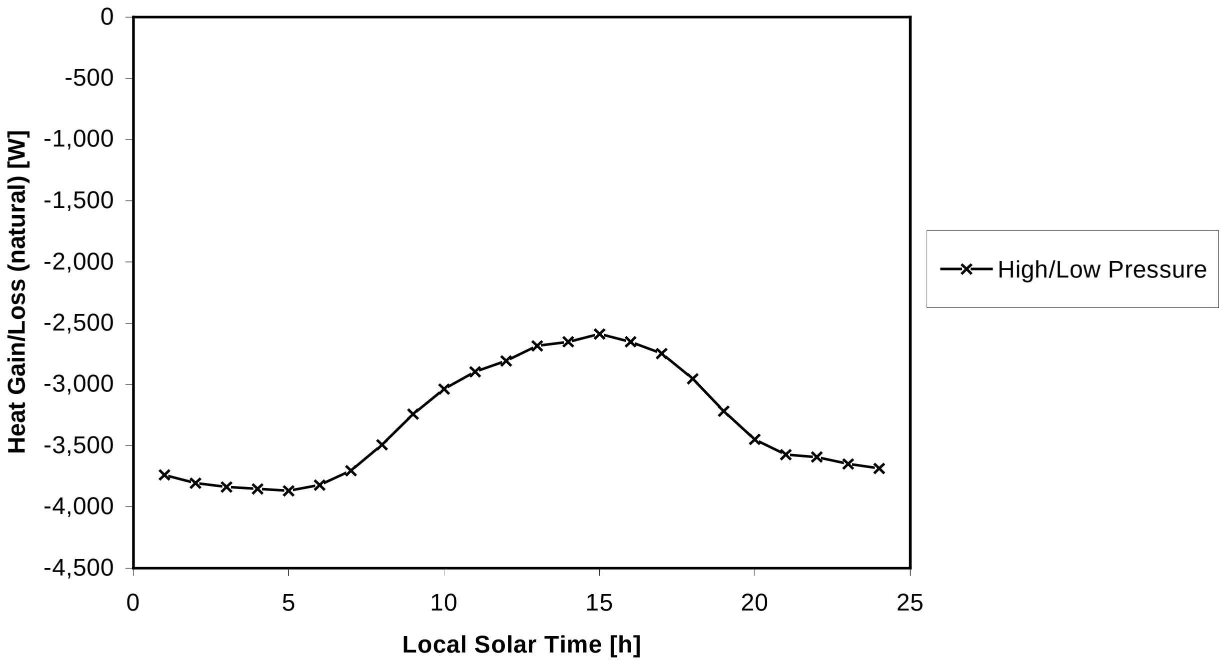


Figure 4-15: Heat Loss of an Opaque Greenhouse (90 m^2 Growth Area) due to Emission at Viking 1 Landing Site during Mid-summer

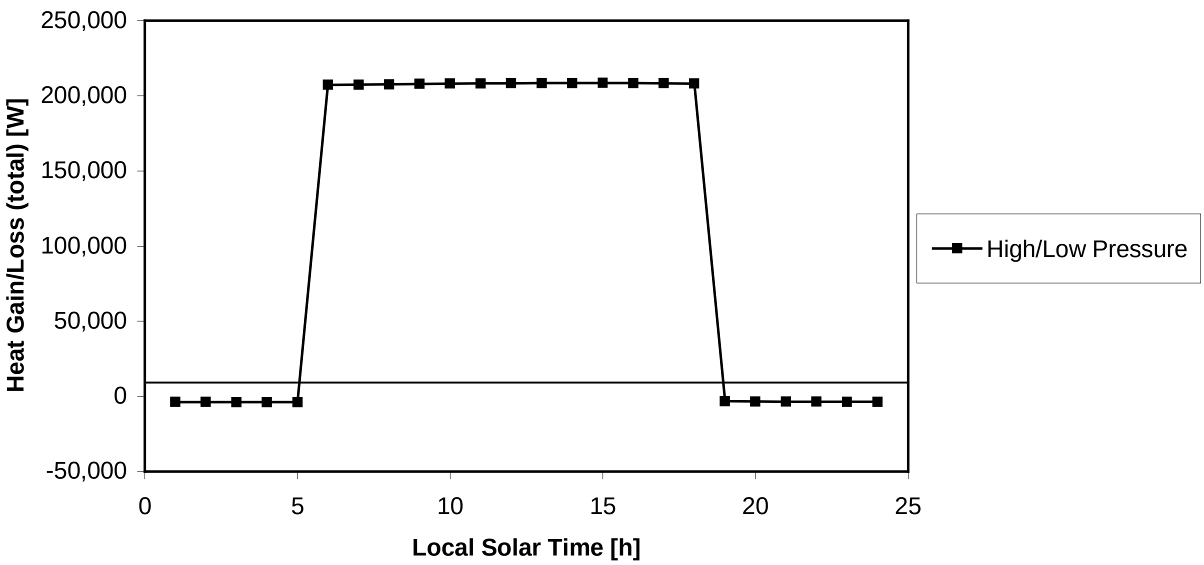


Figure 4-16: Total Heat Gain/Loss for an Opaque Greenhouse (90 m^2 Growth Area) with Artificial Lighting at Viking 1 Landing Site during Mid-summer

Table 4-8: Min./Max./Average Heat Gain/Loss for an Opaque Greenhouse (90 m^2 Growth Area) with and without Lighting at Viking 1 Landing Site during Mid-summer

HEAT GAIN/LOSS	WITHOUT LIGHTS	WITH LIGHTS
Minimum [kW]	-3.9	-3.9
Maximum [kW]	-2.6	208.6
Average [kW]	-3.3	111.1

4.3.3 Greenhouse with Hybrid Lighting

The amount of edible biomass that would be grown increases with increasing the photosynthetically active radiation (PAR) (see section 3.1.5.1). High PAR levels can be achieved by adding artificial electrical light to the natural solar lighting (see section 3.3.4). Figure 4-17 shows the total heat gain/loss of a transparent low pressure (30kPa) greenhouse with an artificial lighting level of 400 µmol/(m^2s) being added to the natural lighting during the Martian day from 6 to 18 hours local solar time. This concept leads to immense cooling requirements during the Martian day and immense heating requirements during the Martian night. The minimum, maximum and average heat gain/loss for this transparent greenhouse with additional artificial lighting during the day are listed in table 4-9.

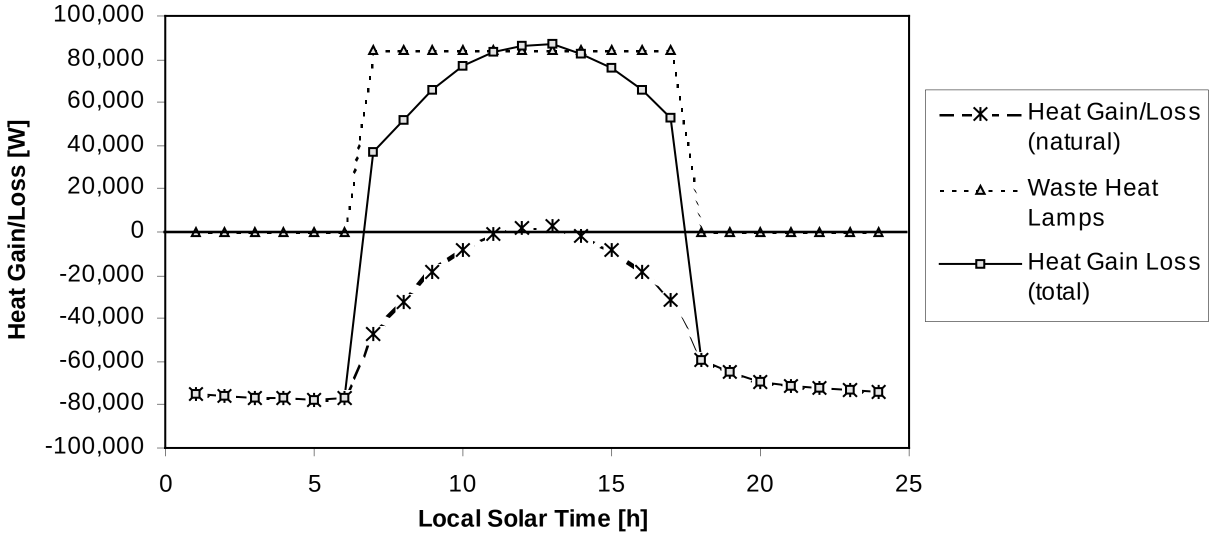


Figure 4-17: Heat Gain/Loss for a Transparent Low Pressure Greenhouse (90 m^2 Growth Area) with Artificial Lighting during the Day at Viking 1 Landing Site during Mid-summer

Table 4-9: Min./Max./Average Heat Gain/Loss for a Transparent Low Pressure Greenhouse (90 m^2 Growth Area) with Artificial Lighting during the Day at Viking 1 Landing Site during Mid-summer

HEAT GAIN/LOSS	VALUE
Minimum [kW]	-77.4
Maximum [kW]	87.0
Average [kW]	-7.3

The immense heat loss during the Martian night can be avoided by covering the greenhouse with a multi-layer insulation (MLI) during the Martian night (see section 4.3.1). Consequently, the heating requirements during the night are relatively low as the emissivity decreases from 1.0 to 0.05. The heat gain/loss for a transparent greenhouse covered with a MLI during the night with additional artificial lighting during the day is shown in figure 4-18. Table 4-10 lists the minimum, maximum and average heat gain/loss for this greenhouse.

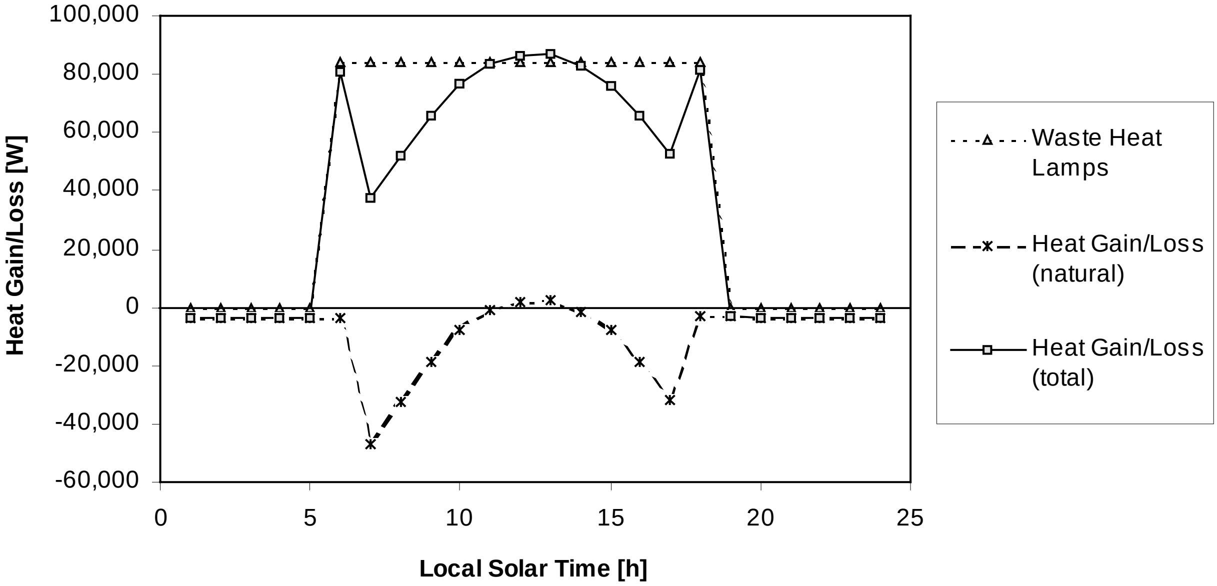


Figure 4-18: Heat Gain/Loss for a Transparent Low Pressure Greenhouse (90 m^2 Growth Area) covered with a MLI during the Night with Artificial Lighting during the Day at Viking 1 Landing Site during Mid-summer

Table 4-10: Min./Max./Average Heat Gain/Loss for a Transparent Low Pressure Greenhouse (90 m^2 Growth Area) covered with a MLI during the Night with Artificial Lighting during the Day at Viking 1 Landing Site during Mid-summer

HEAT GAIN/LOSS	VALUE
Minimum [kW]	-3.9
Maximum [kW]	86.9
Average [kW]	37.0

Regarding the huge heat loss of a transparent greenhouse during the night and the immense waste heat of artificial lighting, a combination of both seems to makes sense. Consequently, the heat loss by emission should be equilibrated by the waste heat of the lamps. This can be achieved by providing an additional artificial lighting level of, e.g., 400 µmol/(m^2s) during the Martian night from 18 to 6 hours local solar time. The diurnal heat gain/loss of this greenhouse concept is shown in figure 4-19. Table 4-11 summarizes the minimum, maximum and average heat gain/loss for this transparent greenhouse with supplemental lighting during the night. The condition for realizing this greenhouse concept would be the selection of plants that need a 24 hour lighting period like, e.g., wheat.

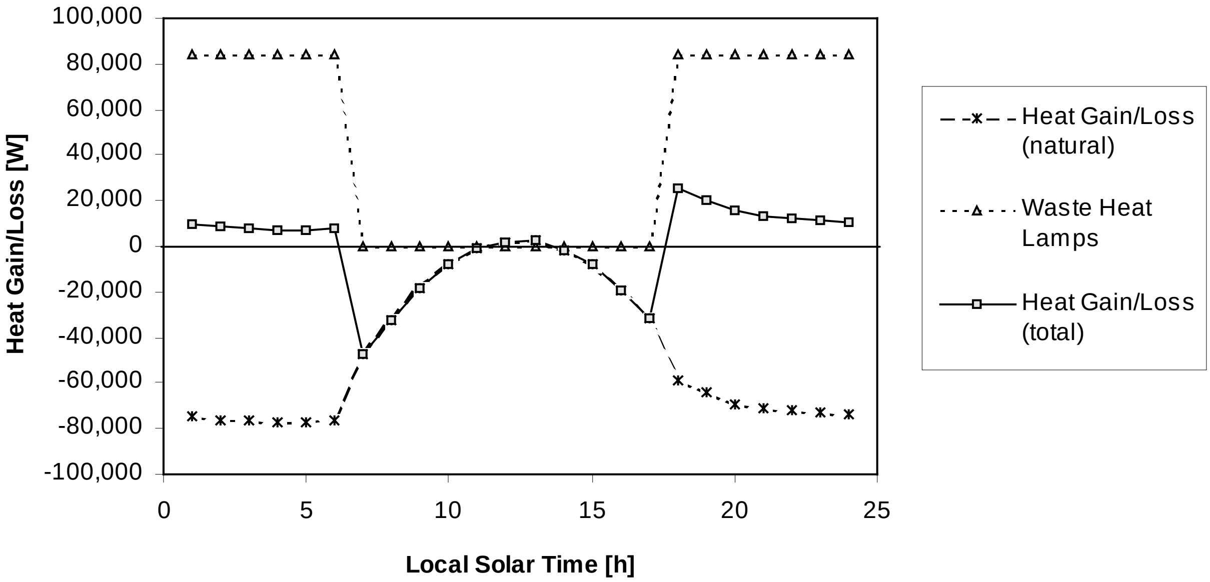


Figure 4-19: Total Heat Gain/Loss for a Transparent Low Pressure Greenhouse (90 m^2 Growth Area) with Artificial Lighting during the night at Viking 1 Landing Site during Mid-summer

Table 4-11: Min./Max./Average Heat Gain/Loss for a Transparent Low Pressure Greenhouse (90 m^2 Growth Area) with Artificial Lighting at Viking 1 Landing Site during Mid-summer

HEAT GAIN/LOSS	VALUE
Min. Heat Gain/Loss [kW]	-47.1
Max. Heat Gain/Loss [kW]	25.4
Average Heat Gain/Loss [kW]	-0.3

4.4 Mass, Power and Cooling Requirements

4.4.1 Equivalent System Mass

Equivalent System Mass is a technique by which several physical quantities which describe a system or subsystem may be reduced to a single physical parameter mass. The primary advantage is to allow comparison of two life support systems with different parameters using a single scale. This is accomplished by determining appropriate mass penalties or conversion factors to convert the non-mass physical inputs into an equivalent mass. For systems which require power, the power system can yield an appropriate power-mass penalty by dividing the average power plant output by the total mass of the generating power system. Similar mass penalties may be determined for other equipment such as thermal control and volume within a pressurized shell. Work is also in progress to define a crew-time-mass penalty to convert maintenance time to mass, but the derivation for this conversion factor is not so obvious. The definition of equivalent mass for a system is the sum of the equipment and consumables commodity mass plus the power, volume, thermal control and crew-time requirements as masses. The infrastructure equivalencies for the Mars Mission are listed in table 4-12. [Drysdale et al., 1999]

Table 4-12: Mars Mission Infrastructure Equivalencies [Drysdale et al., 1999]

EQUIVALENCY	MIN.	NOMINAL	MAX.
Volume [kg/m3]	2.08	2.08	66.7
Power [kg/kW]	54	87	226
Cooling [kg/kW]	58.8	66.7	76.9
Crew-Time [kg/crew-hours]	0.1	TBD	10

The mass required to build the inflatable greenhouse can be divided into the mass of the primary structure, the mass of the secondary structure and the mass of the outfitting/equipment:

- The primary structure contains the material of the semi-cylindrical pneumatic envelope.
- The secondary structure comprises the hatch & bulkhead, cables & anchoring system and the internal flooring system.
- The outfitting includes the growth chambers, active thermal control system, lighting, mechanization, food processing equipment, power management & distribution, utility distribution, information management and communications.

These components are listed in table 4-13. For the equivalent system mass analysis, the mass of those components is required as well as the power, cooling and crew-time requirements.

Table 4-13: Structure/Equipment Components of an Inflatable Mars Surface Greenhouse

Primary Structure	• Bladder • Restraint Layer • Multi-layer Insulation
Secondary Structure	• Hatch & Bulkhead • Cables & Anchoring System • Internal Flooring System
Outfitting/Equipment	• Growth Chamber • Active Thermal Control System • Lighting • Mechanization • Food Processing Equipment • Power Management & Distribution • Utility Distribution • Information Management • Communications

4.4.2 Risk Analysis

The calculation for the equivalent system mass of the greenhouse can be made, by adding the individual values of each subsystem. If a subsystem is not defined precisely and a range of possible values for the mass is given, risk analysis should be considered to determine the range of the total mass and the probability of a value within this range.

In general, risk analysis is a qualitative and/or quantitative method for assessing the impacts of risk on technical situations. The goal of this method is to give a better understanding of the possible outcomes that could occur. The risk analysis process consists of three steps: [@RISK, 1997]

- **Developing a Model** by defining the situation in an Excel worksheet.
- **Identifying Uncertainty** in variables in the Excel worksheet and specifying their possible values with probability distributions and identifying the uncertain worksheet results that have to be analyzed.
- **Analyzing the Model with Simulation** to determine the range and probabilities of all possible outcomes for the results of the worksheet.

The values of the variables are either certain, "deterministic" or uncertain, "stochastic". If the variables are uncertain they have to be described with probability distributions, which will give both the range and the likelihood of occurrence of each value within the range. Two distribution functions for the uncertain values are used in this document: [@RISK, 1997]

- **RiskNormal(mean, standard deviation)** specifies the normal distribution with the entered mean and standard deviation.
- **RiskTriang(minimum, most likely, maximum)** specifies a triangular distribution with three points: a minimum, most likely and maximum. The probability for the most likely value is the highest, the probability of occurrence of the minimum and maximum values are zero.

First, the worksheet has to be examined and the cells containing uncertain values have to be identified. Next, distribution functions for the cells have to be identified. As shown above, the normal and the triangular distribution function are used in this document. If a value is considered to be within a small range and the minimum and maximum value can be identified, the triangular distribution function is used. If only little information about a value is available, the normal distribution function is used, by identifying the average mass and defining a deviation. [@RISK, 1997]

For the equivalent system mass analysis specific physical quantities are required, i.e. nominal values plus a range of possible or observed values. Table 4-14 lists those parameters and their minimum, nominal and maximum values as they are defined in the Baseline Values and Assumptions Document (BVAD). The BVAD provides a baseline for advanced life support modeling and analysis with a common set of initial values and assumptions. [Drysdale et al., 1999]

Table 4-14: Parameters for Equivalent System Mass Analysis [Drysdale et al., 1999]

PARAMETER	MIN.	NOMINAL	MAX.
Lamps/Growth Area for 1000 µmol/(m^2s) [1/m^2]	1.98	5.07	5.56
Ballast Mass [kg/lamp]	4.76	5.00	9.52
Cooling Mass [kg/m^2]	4.43	7.02	25.93
Growth Chamber [kg/m^2]	TBD	40.4	TBD
Mechanization Systems [kg/m^2]	TBD	4.1	TBD
Lamp Power & Ballast Power [kW/lamp]	0.43	0.46	0.48

4.4.3 Equivalent System Mass Analysis

In this document six different greenhouse designs listed in table 4-15 are compared:

- High pressure greenhouse (60 kPa) operated with natural lighting (Option 1)
- Low pressure greenhouse (30 kPa) operated with natural lighting (Option 2)
- High pressure greenhouse (60 kPa) operated with artificial lighting (Option 3)
- Low pressure greenhouse (30 kPa) operated with artificial lighting (Option 4)
- High pressure greenhouse (60 kPa) operated with hybrid lighting (Option 5)
- Low pressure greenhouse (30 kPa) operated with hybrid lighting (Option 6)

Table 4-15: Characteristics of different Greenhouse Design Options

CHARACTERISTICS	LIGHTING	PRESSURE	MATERIAL
Option ①	Natural	High (60 kPa)	Transparent
Option ②	Natural	Low (30 kPa)	Transparent
Option ③	Artificial	High (60 kPa)	Opaque
Option ④	Artificial	Low (30 kPa)	Opaque
Option ⑤	Hybrid	High (60 kPa)	Transparent
Option ⑥	Hybrid	Low (30 kPa)	Transparent

First the equivalent system mass (ESM) of the six greenhouse design options is estimated with average values, then the uncertain values are replaced by probability distributions. With risk analysis simulation the value of the minimum, maximum and average ESM can be calculated (see section 4.4.2).

Table 4-16 lists the mass, power and cooling requirements for the components of the six greenhouse design options. Nuclear power supply is assumed. Furthermore, an equal level of automation and mechanization is assumed for the six greenhouse design options. The ESM for the individual greenhouses providing a growth area of 90 m² is calculated. In order to compare the six greenhouse design options a scenario of greenhouses is assumed, which provides 55% of the required food. If 55% of the required food is produced locally, both the water and the air required for the crew can be regenerated completely (see section 3.1.2).

Supplemental artificial lighting reduces the required growth area and consequently the required number of greenhouses significantly (see figure 3-6). Therefore, the number of greenhouses to provide 55% of the required food is larger for natural greenhouses than for hybrid and artificial greenhouses. The ESM for an assembly of greenhouses providing 55% of the required food is calculated by multiplying the ESM of the individual greenhouse by the required number of greenhouses.

Generally, low pressure greenhouses show a lower ESM than high pressure greenhouses. Furthermore, greenhouses with hybrid lighting have a lower ESM than greenhouses with artificial lighting. Greenhouses operated with natural lighting show the highest ESM values.

Table 4-16: Equivalent System Mass Analysis for Six Greenhouse Design Options

OPTION	①	②	③	④	⑤	⑥	SIMULATION
Transmittance	55%	65%	0	0	55%	65%	
Growth Area [m^2]	90.0	90.0	90.0	90.0	90.0	90.0	
Number of Greenhouses	23.89	15.01	2.39	2.39	4.05	3.68	
Primary Structure [kg]	829.8	616.6	1230.0	1016.8	829.8	616.6	RiskTriang (±10%)
Secondary Structure [kg]	510.0	410.0	510.0	410.0	510.0	410.0	RiskNormal (dev.=10%)
Growth Chamber [kg]	3636.0	3636.0	3636.0	3636.0	3636.0	3636.0	RiskNormal (dev.=10%)
Lamps, Lamp Ballast, Cooling Equipment	0.0	0.0	3629.1	3629.1	1451.6	1451.6	RiskTriang (table 4-14)
Mechanization [kg]	369.0	369.0	369.0	369.0	369.0	369.0	RiskNormal (dev.=10%)
Food Preparation Equipment [kg]	27.4	43.6	274.1	274.1	161.7	178.0	RiskNormal (dev.=10%)
MASS [kg]	**5372.2**	**5075.2**	**9648.1**	**9334.9**	**6958.1**	**6661.2**	
Lamps, Ballast Lamps [kW]	0.0	0.0	246.7	246.7	98.7	98.7	RiskTriang (table 4-14)
Growth System, Mechanization [kW]	39.6	39.6	39.6	39.6	39.6	39.6	RiskNormal (dev.=10%)
POWER [kW]	**39.6**	**39.6**	**286.3**	**286.3**	**138.3**	**138.3**	
ESM-Power [kg]	**3445.2**	**3445.2**	**24911.9**	**24911.9**	**12031.9**	**12031.9**	
Lamps, Ballast Lamps	0.0	0.0	246.7	246.7	98.7	98.7	RiskTriang (table 4-14)
Growth System, Mechanization	39.6	39.6	39.6	39.6	39.6	39.6	RiskNormal (dev.=10%)
COOLING [kW]	**39.6**	**39.6**	**286.3**	**286.3**	**138.3**	**138.3**	
ESM-Cooling [kg]	**2641.3**	**2641.3**	**19099.1**	**19099.1**	**9224.4**	**9224.4**	
Equivalent System Mass (ESM)							
ESM (Individual Greenhouse) [Mg]	11.46	11.16	53.66	53.35	28.21	27.92	
ESM for 55% Food Supply [Mg]	**273.86**	**167.54**	**128.25**	**127.50**	**114.27**	**102.74**	
RANKING	**6.**	**5.**	**4.**	**3.**	**2.**	**1.**	

Figure 4-20 depicts the contribution of mass, power and cooling to the equivalent mass of one individual greenhouse assuming the **nuclear power option**. Greenhouses with artificial lighting have a significantly higher equivalent mass as more power and cooling is required compared to the greenhouses operated with hybrid and natural lighting.

The equivalent system mass for a greenhouse assembly to provide 55% food supply is depicted in figure 4-21. If greenhouses using natural lighting are chosen a significantly high number of greenhouses has to ensure the food supply since natural greenhouses show lower efficiency/productivity due to the reduced lighting level. Therefore, an assembly of natural greenhouses shows the highest equivalent system mass.

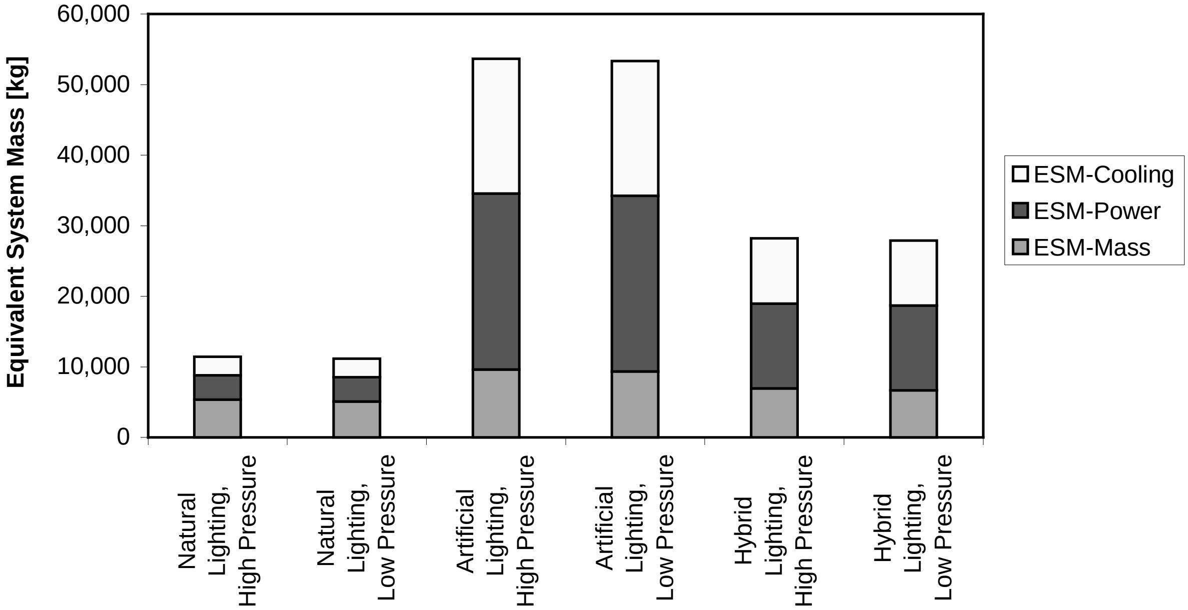


Figure 4-20: Contribution of Mass, Power and Cooling to the Equivalent System Mass of One Individual Greenhouse with a Growth Area of 90 m^2 (assuming nuclear power option)

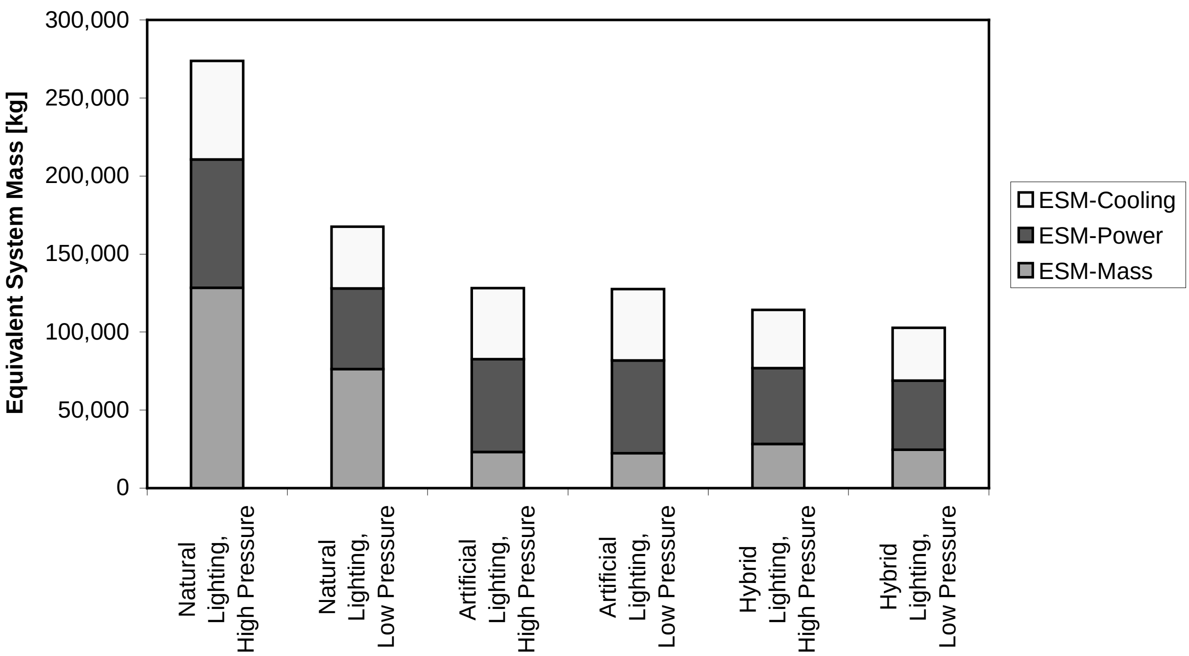


Figure 4-21: Contribution of Mass, Power and Cooling to the ESM of a Greenhouse Assembly Providing 55% Food Supply (assuming nuclear power option)

Table 4-17 shows the risk analysis results for the greenhouse design options assuming the **solar power supply option**. If solar power generation is selected the equivalent mass for power increases. Figure 4-22 depicts the contribution of mass, power and cooling to the equivalent system mass of a greenhouse assembly assuming the solar power option.

Table 4-17: Contribution of Mass, Power and Cooling to Equivalent System Mass (assuming solar power option)

OPTION	①	②	③	④	⑤	⑥
ESM-Mass [Mg]	128.4	76.1	23.1	22.3	28.2	24.5
ESM-Power [Mg]	165.6	104.0	119.8	119.8	98.0	89.1
ESM-Cooling [Mg]	63.1	39.6	45.6	45.6	37.3	34.0
ESM for 55% Food Supply [Mg]	**357.2**	**219.7**	**188.5**	**187.7**	**163.6**	**147.5**
RANKING	**6.**	**5.**	**4.**	**3.**	**2.**	**1.**

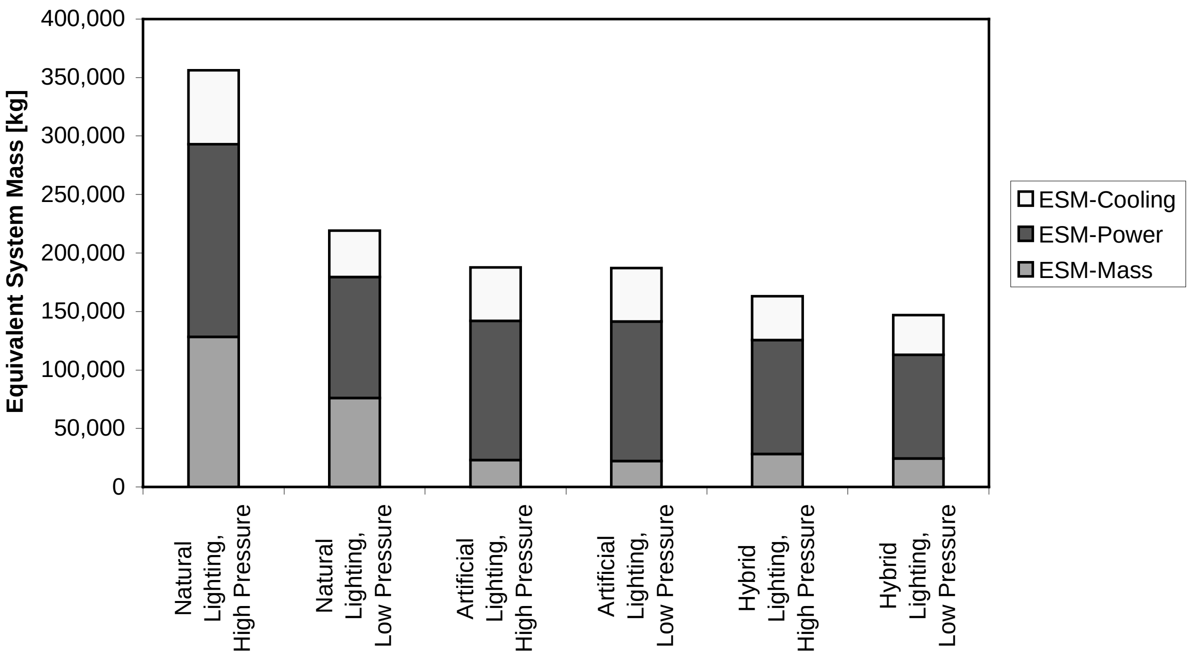
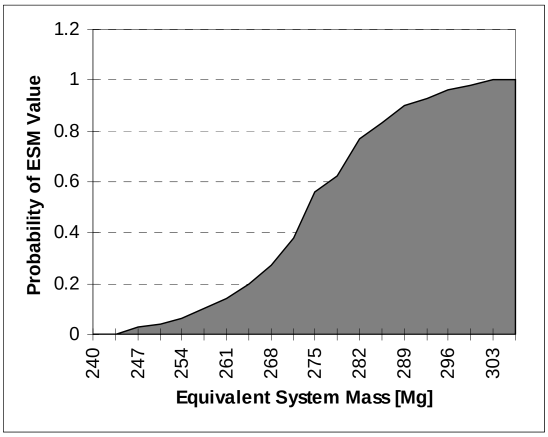
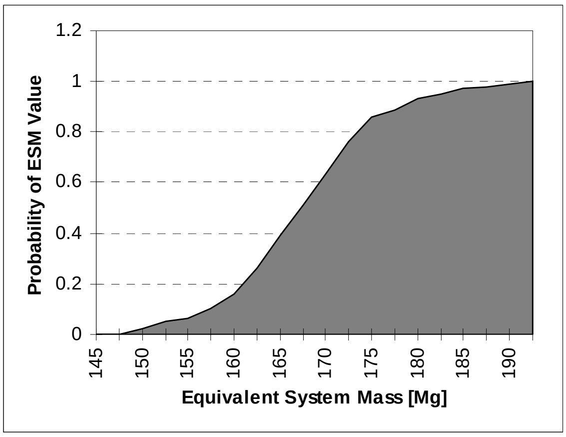


Figure 4-22: Contribution of Mass, Power and Cooling to the ESM of a Greenhouse Assembly Providing 55% Food Supply (assuming solar power option)

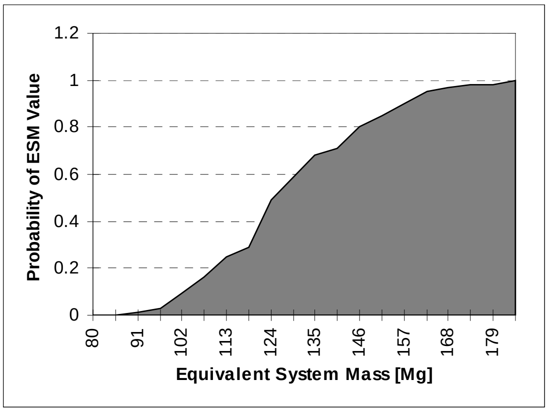
The probability distributions of the equivalent system mass for the six greenhouse design options are shown in figure 4-23. The range of the ESM results and the likelihood of occurrence of each value within the range is given. For example, there is a 40% probability that the equivalent system mass of a high pressure greenhouse operated with natural lighting (option 1) is lower than 274 Mg.



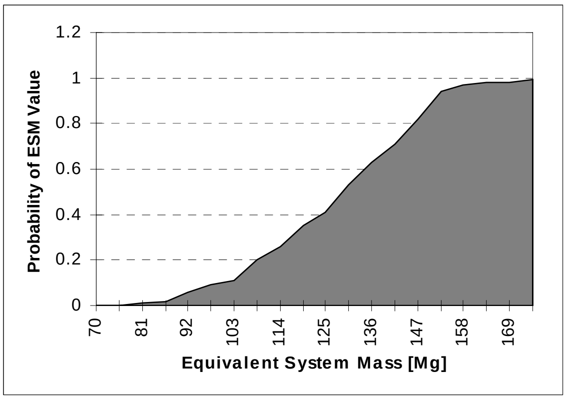
Option 1: Natural Lighting, High Pressure



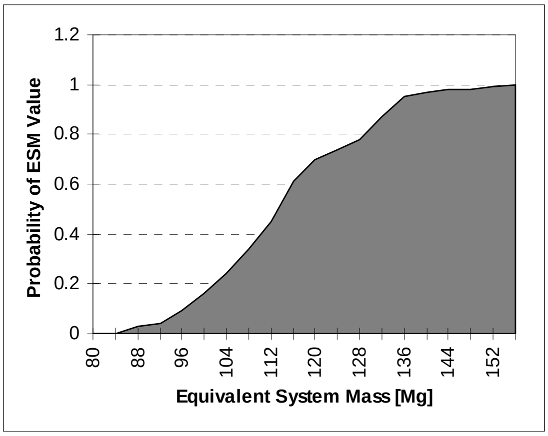
Option 2: Natural Lighting, Low Pressure



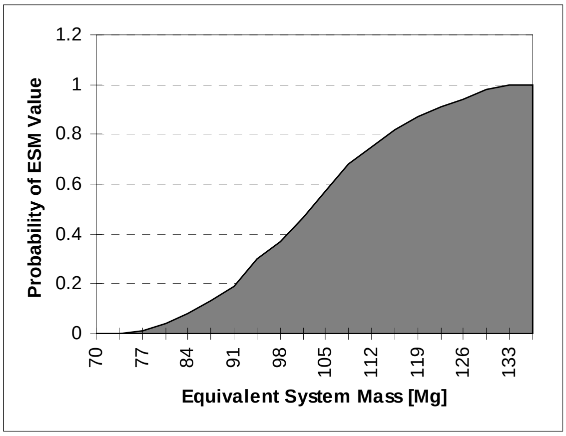
Option 3: Artificial Lighting, High Pressure



Option 4: Artificial Lighting, Low Pressure



Option 5: Hybrid Lighting, High Pressure



Option 6: Hybrid Lighting, Low Pressure

Figure 4-23: Distribution of Equivalent System Mass for Greenhouse Design Options (assuming nuclear power option)

Table 4-18 and figure 4-24 show the range for the equivalent system mass value for the six greenhouse design options.

Table 4-18: Minimum, Mean and Maximum Equivalent System Mass for Greenhouse Design Options (assuming nuclear power option)

OPTION	EQUIVALENT SYSTEM MASS	MINIMUM [Mg]	MEAN [Mg]	MAXIMUM [Mg]
①	Nat. lighting, high pressure	242.6	273.9	301.4
②	Nat. lighting, low pressure	147.3	167.5	191.0
③	Art. Lighting, high pressure	87.1	128.2	181.0
④	Art. Lighting, low pressure	79.7	127.5	178.3
⑤	Hybrid lighting, high pressure	82.4	114.3	154.9
⑥	Hybrid lighting, low pressure	73.7	102.7	131.5

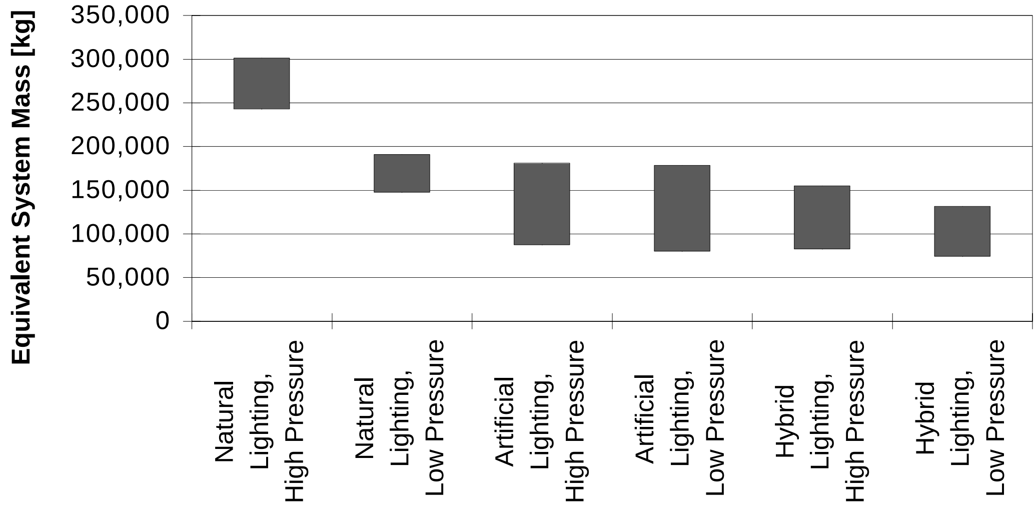


Figure 4-24: Range for Equivalent System Mass for Greenhouse Design Options (assuming nuclear power option)

4.5 Crew-Time Requirements

Crew-time is an important factor for any human mission. Historically, crew-time for life support functions has been limited to monitoring equipment and infrequently replacing expendables. Support for plant systems, however, could easily consume a substantial fraction of the crew-time if designed with inadequate automation. The period of time used to maintain, repair and support life support functions has to be analyzed. These activities involving crew-time are the following: [Drysdale et al., 1999]

- **Maintenance**
  - Servicing and Harvesting:
    The crew requires 3.28 hours per day for servicing and harvesting of the crop, resulting in 0.53 hours per day and per person assuming a crew of 6.
  - Monitoring and Control:
    For monitoring and control it is assumed that the crew requires 0.5 hours per day or 0.083 hours per day and person assuming a crew of six.

- **Repair**
  - Lighting:
    The lamps have a cycle life of 20,000 hours. If artificial lighting is chosen for a greenhouse with a growth area of 90 m^2 459 high pressure sodium lights would be required to provide a lighting level of 1000 µmol/(m^2s). The crew-time to change out lamps is estimated at 0.03 hours. Therefore, a crew-time requirement is estimated at 0.0166 hours per day or 0.0028 hours per day and per person.

  - Structure:
    The crew-time requirement for repairing the structure is assumed to be 0.02 hours per day or 0.033 hours per day and per person assuming a crew of six.

- **Support**
  - Food Preparation & Processing:
    It is assumed that each crew member eats ten different dishes per day. For a crew of six, each dish prepared using ingredients provided by bioregenerative methods requires 30 minutes on average to prepare. Consequently, a diet based on crops grown in the greenhouse would require 5.0 hours per day preparation and processing time, or 0.83 hours per day and person assuming a crew of six. In comparison to this, a meal prepared from resupplied items takes 6 minutes to prepare, resulting in crew-time requirement of 1 hour per day or 0.17 hours per day and person assuming a crew of six.

Table 4-19 shows both the crew-time estimate for the total crew and for the individual crew member assuming a crew of 6.

Table 4-19: Crew-Time Estimate (90 m^2 Growth Area) [Drysdale et al., 1999]

ACTIVITY	TIME
Maintenance	
Servicing and Harvesting	3.28 h / (day x crew) 0.53 h / (day x person)
Monitoring and Control	0.50 h / (day x crew) 0.083 h / (day x person)
Repair	
Lighting	0.0166 h / (day x crew) 0.0028 h / (day x person)
Structure	0.020 h / (day x crew) 0.0033 h / (day x person)
Support	
Food Preparation & Processing	5 h / (day x crew) 0.83 h / (day x person)
TOTAL CREW-TIME REQUIREMENT	**8.82 h / (day x crew)** **1.47 h / (day x person)**

5 Alternative Design Ideas

There are many alternative design ideas that have to be evaluated in the future. One important issue is the implementation of Vectran instead of Kevlar as the restraint layer material. The superb abrasion resistance demonstrated by Vectran during folding and unfolding cycles coupled with high tenacity combine to make Vectran the current leading candidate material. The material has also exhibited excellent resistance to long term radiation damage. Kevlar has been used for the TransHAB since it was more economical and since it has been further tested and developed. [Kennedy, 2000]

The advantage of covering a transparent greenhouse during the night has been discussed in section 4.3. It should be worked on a concept how the night time insulation has to be deployed over the greenhouse.

The bladder and restraint layer will most likely not provide sufficient radiation protection for humans. Therefore, radiation protection methods should be considered. An opaque greenhouse could be buried in regolith in order to stop the hazardous radiation to penetrate into the greenhouse. In addition, the regolith would insulate the greenhouse from the varying temperatures on the surface of Mars. An option to prevent human and plant radiation exposure inside a transparent greenhouse would be a water barrier. It could be realized by flooding water in between the individual layers of an external cavity shell separate from the redundant bladder assembly and the restraint layer. Furthermore, a water barrier filters out infrared wavelengths. It also helps storing heat if the multi-layer night time insulation is used outside of the water. This water barrier concept has the advantage that the area to be protected can be selected and controlled. Furthermore, the thickness of the protective layer and the fluid density can be varied. The disadvantages of the water barrier include the reduced transmissivity of the greenhouse shell, the required ports, valves and lines. This water barrier may have to be kept warm to avoid the freezing of the fluid. [Ewert, 2000; Kennedy, 1999]

An alternative method of storing heat would be a louver installed outside of the greenhouse. It will be opened during the Martian day and the blades follow the direction of the sun. During the night the louver will be closed. Consequently, the heat will be reflected by the louver inside and, therefore, it is kept inside of the greenhouse.

If artificial lighting is chosen, highly efficient lighting would be desirable. The development of higher output efficiency, robust and safe lighting is important for the success in food production. The emerging technology of light emitting diodes (LED) integrated into solid state lighting systems is very promising for growth chambers and greenhouses. In addition, more layers of crops may be used in order to utilize the volume of the greenhouse efficiently. [Kennedy, 1999]

The greenhouse should be fully integrated into the Mars surface infrastructure. In addition to the exchange of air and water, thermal heat sharing should also be considered. It has to be investigated if waste heat produced by other modules can be used when the greenhouse needs to be heated. Concepts should be developed to collect, distribute and exchange waste heat produced by internal systems and other modules in order to keep the greenhouse environment in an optimum growing temperature. [Kennedy 1999]

Pressure loss is a risk that can have fatal consequences for the crew and the plants. An option to avoid the shell from deflating would be a rigid interior support structure. The disadvantage would be the additional mass resulting in higher launch costs. A more economic way to avoid the event of catastrophic decompression would be the use of an air-supported structure (see section 3.2.1). The greenhouse would consist of two chambers: the inner chamber where the plants are grown shares the atmosphere with the other pressurized modules, and the outer chamber where the atmosphere of Mars is concentrated from outside to provide a carbon dioxide rich environment. In the case of a depressurization of the inner atmosphere, the outer membrane of the carbon dioxide atmosphere would be able to capture the escaping oxygen atmosphere while the crew evacuates the chamber. The second atmosphere would not only be very important from a safety standpoint but also extremely important for the thermal system. If the extreme cold temperatures of Mars come in contact with the humid atmosphere of the plant growth chamber, condensation and precipitation occur. This results in condensation forming on the membrane and loss of transparency, reducing available light for plant growth. [Sadler, 1999]

Two greenhouse concepts were presented at the Inflatable Mars Greenhouse Workshop at the Kennedy Space Center in December 1999:

The inflatable greenhouse "Torus-Concept" is an inflatable structure that combines both a high pressure (60-70 kPa) environment for humans and a low pressure (20-35 kPa) environment for plants. A 2.5 - 3 m inner diameter torus circumscribes the larger low pressure greenhouse at the ground level. By splitting the functions into the human area and the greenhouse area the inflatable structure can be optimized and is therefore more efficient and lighter.
The torus section incorporates the interface to an airlock or habitat, utility interfaces and distribution, human viewing ports and workstations for monitoring and tending crops. The dome section encapsulates the torus and provides the plant growth area. This concept is depicted in figure 5-1. [Kennedy, 1999]

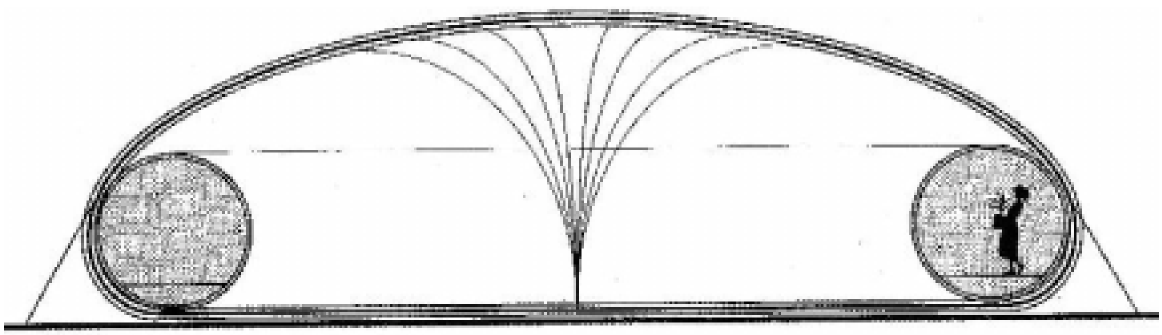


Figure 5-1: Inflatable Greenhouse Torus-Concept [Kennedy, 1999]

Another concept presented at the workshop was a growing system consisting of plants being grown in plastic membrane bags suspended from support wires with nutrient solution flowing to the plant roots. This growing system is based on relatively lightweight and flexible material, wire and plastic membrane material, that can be compressed and included into the uninflated greenhouse while stowed during the transit and returned to their proper orientation upon inflation. Suspending membrane bags along an uninterrupted wire allow the plants of that row to be drawn along the wires towards an end point where a harvesting device may be located. The advantage of this "Wire Culture-Concept" is that the food production works for extended periods in an autonomous mode. If a crew member has to enter the greenhouse the moveable wire support structure allows the plants to be rotated upwards in order to produce a walking space in between the wires holding the plants growing in bags. Once the crew member exits the greenhouse, the wire frames return to their original position and the walkway disappears, maximizing the growth area. This sequence is shown in figure 5-2. [Sadler, 1999]

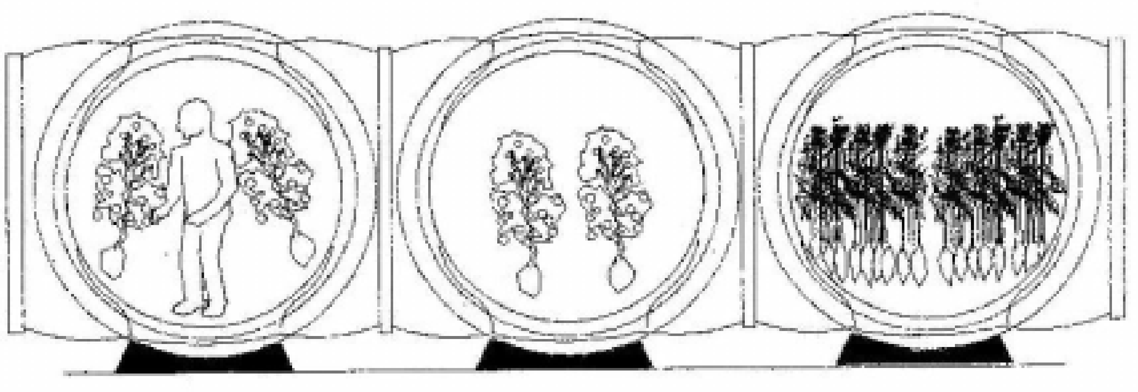


Figure 5-2: Wire Culture Concept [Sadler, 1999]

6 Mars Greenhouse Research, Technology and Development Roadmap

In December 1999 a roadmap for future testing needed for the design of a Mars greenhouse was developed at the Inflatable Mars Greenhouse Workshop at the Kennedy Space Center. The required studies were ordered with priority and put in a time scheme regarding early, mid-term and long-term studies.

Near-term studies:

- **Test of photo-synthetically active radiation (PAR) on Mars.** This test can be realized by sending a small experiment to the surface of Mars with a probe that tests the PAR level on the surface of Mars and the PAR level in an inflatable structure.
- **Material test in Mars environment.** This test can either be simulated on Earth or with gravity aspect on Mars.
- **Development of Mars atmosphere model.** The data of the model will be used as input for the studies on the thermal system.
- **Studies on plants.** The lower limits of pressure, temperature, light and gravity requirements of plants in regards to edible biomass have to be studied. Furthermore, studies on the plant responses concerning vapor, high CO_2 level and composition of atmosphere have to be done.
- **Start of trade studies.** Trade studies, e.g. edible volume vs. equivalent system mass (ESM), have to demonstrate the feasibility of the greenhouse by proving the cost effectiveness, i.e. the cost and risk of growing the plants in-situ has to be less than the cost and risk of shipping them. Early trade studies will still be based on many assumptions as there is not enough input data available. By progressing this roadmap the results will be improving.

Mid-term studies:

- **Design requirements.** The design requirements on the greenhouse, e.g. growing area, have to be defined.
- **ISS tests.** The results of tests in the International Space Station (ISS) have to be used as input for new trade studies and new ideas. The Autonomous Garden Pod (AG-Pod), a pressurized plant growing module, will be flown and the experimental data will contribute to the greenhouse design.
- **Studies on automation and maintenance of biomass production chambers.** Data and experience gathered by the BIO-Plex tests have to be considered for the greenhouse design.
- **Single plant growth units on Mars.** Experiments on future Mars landers have to be developed, the earliest possibility would be the 2005 Mars lander.
- **Continuation of trade studies.** The trade studies have to be continued with more precise input. The results indicate the direction for further studies on plants, materials and structures.

Long-term studies:

- **Building and testing of greenhouse structure.** A full-size greenhouse has to be tested under Martian conditions. It has to provide sufficient gas retention, structural restraint, micro-meteoroid protection, thermal protection and radiation protection.

The vision of the development of the greenhouse is to provide a biological component for long-term life support in order to establish permanent human settlement on Mars. The long-term vision foresees the regeneration of the Martian atmosphere making the planet more habitable for humans and plants. The technologies developed for the greenhouse should not be applicable exclusively to Mars. The new technologies and experience gained by the development of a Mars greenhouse will also bring benefits to life on Earth as they help developing technologies for surviving in hostile environments such as oceans.

7 Conclusions and Recommendations

In this document six different greenhouse designs according to section 4.4.3 are compared:

- High pressure greenhouse (60 kPa) operated with natural lighting (Option 1)
- Low pressure greenhouse (30 kPa) operated with natural lighting (Option 2)
- High pressure greenhouse (60 kPa) operated with artificial lighting (Option 3)
- Low pressure greenhouse (30 kPa) operated with artificial lighting (Option 4)
- High pressure greenhouse (60 kPa) operated with hybrid lighting (Option 5)
- Low pressure greenhouse (30 kPa) operated with hybrid lighting (Option 6)

These six greenhouse options are compared according to the design criteria defined in section 4.1, including **performance, safety, technology, schedule and cost**. For each criteria the total score of 100 % is distributed among the six design options. The better the greenhouse fulfils the criteria the higher is the score.

Regarding the strategic objectives, greenhouses operated with artificial lighting (option 3, 4) have the advantages of being applicable to multiple destinations, including the moon, as they do not depend on the solar lighting, resulting from a day-night cycle comparable to the 24 hour Earth day. If the mission objectives are changed, e.g. the mission duration or number of crew members, greenhouses operated with hybrid and artificial lighting (options 3,4,5,6) are more flexible as the photo-period can be shortened/extended and/or the lighting period can be changed according to the productivity requirements. Assuming a food supply of 55% by in-situ food production, the number of launches is significantly higher for greenhouses operated with natural lighting (options 1,2) than for the greenhouses utilizing artificial or hybrid lighting (options 3,4,5,6) as the required number of greenhouses is higher for natural greenhouses (see section 3.1.5.1). The number of launches for low pressure greenhouses (options 2,4,6) is lower than for high pressure greenhouses (option 1,3,5) as the total mass decreases with decreasing pressure. Table 7-1 shows that a low pressure (30 kPa) greenhouse operated with artificial lighting (option 4) would be the best solution in terms of performance.

Table 7-1: Performance Evaluation Matrix

PERFORMANCE 10%	**WEIGHT**	①	②	③	④	⑤	⑥
Strategic Objectives	50%	10.0%	10.0%	30.0%	30.0%	10.0%	10.0%
Mission Objectives	35%	10.0%	12.0%	15.0%	18.0%	21.0%	24.0%
Number of Launches	15%	4.0%	8.0%	24.0%	28.0%	14.0%	22.0%
SCORE		**9.1%**	**10.4%**	**23.9%**	**25.5%**	**14.5%**	**16.7%**

High pressure greenhouses (options 1,3,5) bear less risk for the crew in case of an abort scenario as, e.g., the crew has more time to abort the greenhouse in case of decompression. The highest redundancy is provided by the greenhouse operated with hybrid lighting (options 5,6). It relies on both artificial and solar lighting, i.e., in case of a power breakdown or a major Martian dust storm it is still productive. Hazards are less likely to occur in a greenhouse operated with natural lighting (options 1,2). As lower power and no lighting is required less hazards may arise from a reduced internal outfitting. As shown in table 7-2 high pressure greenhouses (options 1,3,5) best ensure crew safety and productivity for all mission phases.

Table 7-2: Safety Evaluation Matrix

SAFETY 30%	**WEIGHT**	①	②	③	④	⑤	⑥
Abort Scenarios	25%	17.0%	16.3%	17.0%	16.3%	17.0%	16.3%
Redundancy	25%	15.0%	15.0%	15.0%	15.0%	20.0%	20.0%
Hazards	25%	20.0%	20.0%	15.0%	15.0%	15.0%	15.0%
Crew Issues	25%	16.0%	12.0%	22.0%	18.0%	18.0%	14.0%
SCORE		**17.0%**	**15.8%**	**17.3%**	**16.1%**	**17.5%**	**16.3%**

All six greenhouse design options tend to have the same architecture sensitivity, as they all depend on specific technologies. The technology maturity is more advanced for the high pressure greenhouses (options 1,3,5) since more experience is available for high pressure plant growth. If primary technologies or technical approaches are not available the likelihood for the availability of alternative technologies tends to be the same for all six greenhouse design options. Regarding the technology design criteria the high pressure greenhouses (options 1,3,5) have a significantly lower technology risk as shown in table 7-3.

Table 7-3: Technology Evaluation Matrix

TECHNOLOGY 25%	**WEIGHT**	①	②	③	④	⑤	⑥
Architecture Sensitivity	30%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%
Technology Maturity	30%	18.0%	14.0%	20.0%	16.0%	18.0%	14.0%
Risk Mitigation	40%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%
SCORE		**17.1%**	**15.9%**	**17.7%**	**16.5%**	**17.1%**	**15.9%**

High pressure greenhouses (options 1,3,5) need less time for the development of required technologies, for the system development and for the integration of a planned launch date as they have a higher technology maturity level. The time for pre-launch processing is significantly higher for greenhouses operated with natural lighting (options 1,2) as the projected number of launches is higher than for greenhouses operated with artificial lighting. Table 7-4 indicates that low pressure greenhouses (options 2,4,6) need to start design and development activities significantly earlier.

Table 7-4: Schedule Evaluation Matrix

SCHEDULE 5%	**WEIGHT**	①	②	③	④	⑤	⑥
Technology Development	30%	18.0%	14.0%	20.0%	16.0%	18.0%	14.0%
System Development & Integration	40%	18.0%	14.0%	20.0%	16.0%	18.0%	14.0%
Mission/Launch/ Processing	30%	14.0%	14.0%	19.0%	19.0%	17.0%	17.0%
SCORE		**16.8%**	**14.0%**	**19.7%**	**16.9%**	**17.7%**	**14.9%**

Low pressure greenhouses (options 2,4,6) have the disadvantages of a lower technology readiness level. Furthermore, much new technology development will be required to realize a low pressure greenhouse. High pressure greenhouses (options 1,3,5) have a higher mass compared to low pressure greenhouses. The method of lighting and internal pressure does not impact the required ground facilities to support the proposed greenhouse. The costs for low pressure greenhouses arising from the first mission and subsequent missions are lower than for high pressure greenhouses; they are the lowest for greenhouses operated with natural lighting (options 1,2). The non-recurring costs also tend to be lower for low pressure greenhouses and the lowest for greenhouses operated with natural lighting. All six greenhouses could share costs with other modules, e.g., waste heat. Greenhouses using natural lighting are the most efficient in terms of costs as demonstrated in table 7-5.

Table 7-5: Cost Evaluation Matrix

COST 30%	**WEIGHT**	①	②	③	④	⑤	⑥
Technology	20%	20.0%	12.0%	22.0%	14.0%	20.0%	12.0%
Systems	25%	21.0%	24.0%	10.0%	12.0%	15.0%	18.0%
Facilities	5%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%
Recurring Costs	20%	7.0%	14.0%	16.0%	18.0%	21.0%	24.0%
Non-recurring Costs	25%	7.0%	14.0%	16.0%	18.0%	21.0%	24.0%
Cost Sharing Potential	5%	16.7%	16.7%	16.7%	16.7%	16.7%	16.7%
SCORE		**14.1%**	**16.4%**	**15.8%**	**15.6%**	**18.9%**	**19.4%**

Table 7-6 lists the final results of the greenhouse design comparison. The high pressure greenhouses operated with artificial lighting or hybrid lighting show the best results. The low pressure greenhouses operated with hybrid or artificial lighting are in third and forth place. The high and low pressure greenhouses operated with natural lighting have the lowest score. Figure 7-1 depicts the final ranking.

Table 7-6: Greenhouse Design Comparison Evaluation Matrix

DESIGN CRITERIA	**WEIGHT**	①	②	③	④	⑤	⑥
Performance	10%	9.1%	10.4%	23.9%	25.5%	14.5%	16.7%
Safety	30%	17.0%	15.8%	17.3%	16.1%	17.5%	16.3%
Technical	25%	17.1%	15.9%	17.7%	16.5%	17.1%	15.9%
Schedule	5%	16.8%	14.0%	19.7%	16.9%	17.7%	14.9%
Cost	30%	14.1%	16.4%	15.8%	15.6%	18.9%	19.4%
FINAL SCORE		**15.3%**	**15.4%**	**17.7%**	**17.0%**	**17.5%**	**17.1%**
Ranking		**6.**	**5.**	**1.**	**4.**	**2.**	**3.**

High pressure greenhouses show better results than low pressure greenhouses, except for the natural lighting method, as they have a higher technology readiness level and are considered to be safer. By continuing the studies on low pressure plant growth and technologies to ensure the safety of low pressure greenhouses the results of the low pressure greenhouses will be improving and will possibly be better than the high pressure greenhouses as they offer the advantages of both mass reduction and higher flexibility.

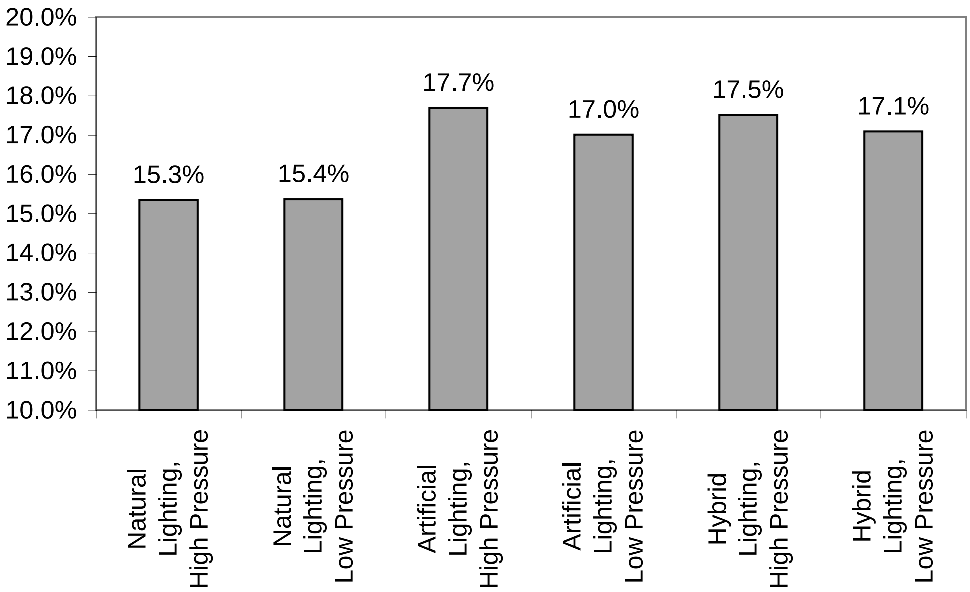


Figure 7-1: Greenhouse Design Comparison

The results of this study depend strongly on the assumptions defined in this document. Further evaluation and testing is required in order to improve these assumptions. It is very important to continue the plant studies, especially the impact of low pressure, low light level, hybrid lighting and radiation effects on plants. Furthermore, operational experience gained by the BIO-Plex project has an important impact on the greenhouse design. The development of inflatable structures and materials, e.g. the TransHAB development, has to be monitored for future greenhouse designs.

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